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R-367

A MULTIRANGE PRECISION TORQUE MEASURING DEVICE

by

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July 1962

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ABSTRACT

A precision torque-measuring system for torques ranging from 0.010 to 1000 dyne-centimeters is described. The unknown torque is measured by a feedback system which automatically develops a balancing torque by means of an electromagnetic torque generator. The inphase product of the primary excitation and the secondary feedback current into the torque generator to develop this balancing torque is the measure of the unknown torque. A dynamometer-type wattmeter or Hall Effect current product device is used to measure the inphase current product. By the proper use of a decade attenuator in the torque generator feedback circuit and by the adaptive control of the system elastance, the wide range of torques can be measured to a precision of about 0.1 percent of full scale.

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CHAPTER 1

INTRODUCTION

1.1 Basic Definitions

The concept of torque is as old as machines. Man learned early to lubricate his wheel bearings with animal fats to reduce frictional torques. The ancient Roman engineers were vitally interested in torque principles, particularly in regard to their catapults for throwing stones and other missiles at enemy fortifications. These engines operated on the principle where the "throwing arm" was wound up into the ready condition by means of energy storage in leather strips in torsional tension. Since that time man has employed a variety of methods in developing machines wherein torque plays an important part. In short, any device with a rotating part is involved with a torque. As machines became more sophisticated, man wanted to understand torque in its quantative sense.

Torque is defined as the mechanical energy per unit angle absorbed by a body when rotated in a given sense about a given axis. Energy can be received by a body in three general ways, namely:

1. Inertially; $I_b \left(\frac{d^2 A_b}{dt^2} \right)$

2. Viscously; $C_b \left(\frac{d A_b}{dt} \right)$

3. Elastically; $K_b A_b$

Where I_b is the moment of inertia of the body about its axis of rotation under consideration, C_b is the damping coefficient of the body with respect to its boundary environment, and K_b is the elastance of the body with respect to a fixed reference frame. A_b is defined as the angular displacement of the body about its axis of rotation from some zero or reference orientation.

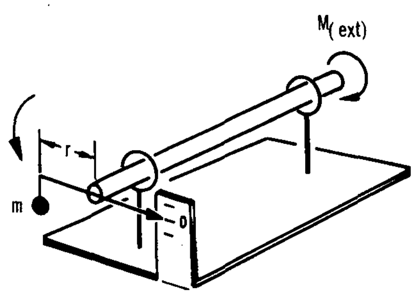
A ballistic galvanometer is an example of energy or torque absorption in the inertial sense.

A watt-hour meter is an example of energy or torque absorption in the viscous sense.

A watch or clock escapement with a hair-spring is an example of energy or torque absorption in the elastic sense.

Measurement of torque in either sense involves the knowledge of the body's angular displacement or its time derivatives. Torque may also be directly measured by means of a torque balance where the energy absorbed is matched by a negative torque applied in the same manner, as for example, in a stalled motor test or chemical balance measurement. Many means of measurement have been devised, but they usually fall into either of two main categories as follows (see Fig. 1-1):

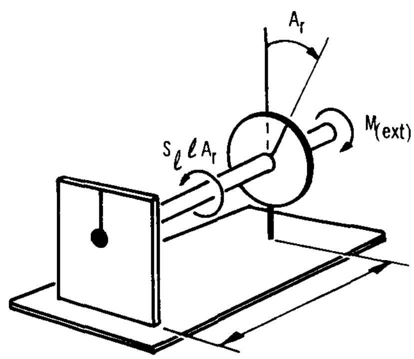
1. The gravitational-mass balance method.
2. The stress-strain balance method.



$M_{(ext)} + mgr = 0$

$M_{(bal)} = mgr$

a) Primary measurement of torque by gravitational method



$M_{(ext)} + S_\ell \ell A_r = 0$

S = elastic coefficient per unit length

$M_{(bal)} = S_\ell \ell A_r$

b) Secondary measurement of torque by stress-strain method

Fig. 1-1. Gravitational and stress-strain balance methods of measuring torque.

In the gravitational-mass balance method a rigid single-degree-of-freedom rod, supported in the horizontal plane, is acted on by a torque to be measured. A means for detecting the angular deflection or rotation of the rod about its cylindrical axis is provided. The angular deflection caused by the applied torque is brought back to its original zero position by means of hanging a known mass at a known radius arm from the axis of rotation. In this case, the measured torque is the product of the mass times the acceleration of local gravity times

the radius arm, as follows:

$$\boxed{M_{(bal)} = \text{balancing moment} = mgr} \qquad (1\text{-}1)$$

where

mg = weight or force of balancing mass

r = radius arm of the mass m

This is known as a primary measurement because only the mass, m, the acceleration of gravity, g, and the length, r, need to be measured. An analytical balance used in chemistry is an excellent example of the gravitational-mass balance method of measuring torque.

In the stress-strain balance method a non-rigid elastic single-degree-of-freedom rod of length l, is supported in any general orientation with one end fixed to an arbitrary rigid reference frame. A means for measuring the angular deflection or rotation of the free end with respect to the fixed end, about its cylindrical axis, is provided. The torque to be measured is applied at this free end. This applied torsional stress causes the rod to "twist" or strain until this elastic deformation results in an equal and opposite developed torque which balances the applied torque.

In this case the measured torque is equal to the product of the rod's elastic constant, times the angular deflection of the free end of the rod with respect to the fixed end at the reference frame, as follows:

$$\boxed{M_{(bal)} = \text{balancing moment} = S_{(rod)}\, A_r} \qquad (1\text{-}2)$$

where

$S_{(rod)}$ = elastic coefficient of the rod

A_r = angular deflection of the free end with respect to the fixed end

This is commonly known as Hooke's Law, and the torsion wire balance is an excellent example of this method of measuring torque.

There is a class of stress-strain balance types where the rod or torque receiver is rigid and one end is coupled to the fixed reference frame by means of an elastic helical spring whose elastic constant is known. The usual electric meter movement balance is an example of this stress-strain balance type. The stress-strain balance method is known as a secondary measurement because the elastance of the elastic material must be measured or calibrated.

1.2 Torque-Summing-Member

These methods are suitable for the measurements of torque levels that are high, compared to the frictional or unbalance torques of the rotational shaft, called a "torque-summing-member."[(1)*] When the torque to be measured gets too low, then the environmental, disturbing torques on the measuring equipment are proportionately too high. It now becomes necessary to consider more sophisticated devices to insure proper quantitative results.

The gravitational-mass balance method has been used many times in the measurement of torque. The Instrumentation Laboratory uses this method on occasions when very accurate torque measurements of electromagnetic components are desired. However, these measurements using an analytical balance are so time-consuming that this method was not considered in this torque measuring device under consideration. Instead, variations of the stress-strain balance methods are used.

There is a variation on the stress-strain balance method where instead of measuring the strain or angular deflection of an elastic rod to obtain a measure of torque, a counter-balance torque whose magnitude is known is applied to a rigid rod, or torque-summing-member. In this case the counter-balance torque is made to be a function of the angular deflection. This is known as a feedback torque whose magnitude varies with the rod's angular deflection. This is similar to what occurs in the rigid shaft and helical hairspring employed in the usual ammeter and voltmeter movements. However, in this case, a torque generator is used, whose input quantity – output torque generation characteristics are known. Thus, the angular deflection of the torque-summing-member measured by a device in angular units must be converted by a proper torque generating transducer to produce a counter-balance feedback torque proportional to the angular deflection of the rigid torque-summing-member. The input quantity to this feedback torque transducer is then a steady-state measure of the externally applied torque, as follows:

$$M_{(bal)} = S_{(tg)}\, q_{(in)} \qquad (1\text{-}3)$$

Where $S_{(tg)}$ is the sensitivity of the torque transducer relating torque output, $M_{(bal)}$, to the input quantity, $q_{(in)}$. It only remains to have a device called an angular deflection signal transducer to produce as its output, the input, $q_{(in)}$, to the torque transducer, as follows:

$$q_{(in)} = S_{(sg)}\, A_r \qquad (1\text{-}4)$$

Where $S_{(sg)}$ is the sensitivity of the angular deflection transducer, or signal

*Superscript numerals refer to similarly numbered references in the Bibliography.

generator, relating its output signal, $q_{(in)}$, to its input angular deflection, A_r. This is shown in Fig. 1-2.

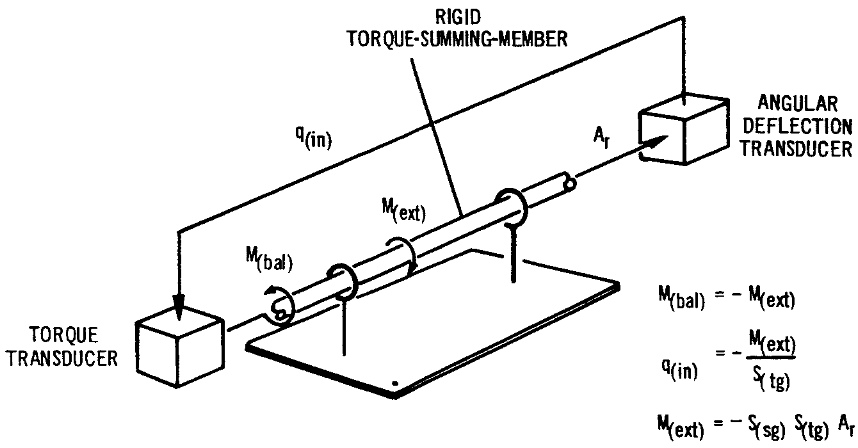


Fig. 1-2. Schematic showing general torque measuring feedback loop.

1.3 Torque-to-Balance Loop

It has been pointed out by Gilinson and Scoppettuolo[2] that a good method of measuring low-level torques is to monitor the excitation required to develop a torque, in an electromagnetic device, equal and in an opposite direction to the applied torque. This is conveniently done in a "closed-loop" system or feedback-control device called a "torque-to-balance loop." The angular deflection of a torque-summing-member, to which a torque has been applied, develops a voltage signal in a device called a microsyn signal generator. This signal is proportional to the angular deflection and in a phase-sense corresponding to the direction of rotation. The signal is then fed into an amplifier which develops enough power to feedback a current into the secondary of another device, attached to the torque-summing-member, called a microsyn torque generator. This current into the secondary winding of the torque generator is caused to flow in such a direction as to develop a balancing torque $M_{(bal)}$, equal and opposite to the external torque being applied to the torque-summing-member. Thus, by measuring this torque generator secondary feedback current, the applied torque can be evaluated.

It will be pointed out in detail, however, that there are many shortcomings to this simple type of measurement. It is the purpose of this paper to describe various methods which circumvent many of these restrictions and allow a very precise measurement of torque, even of low values. In a sense this device is an example of the stress-strain balance method, where the applied torque causes a rotational strain or angular displacement of the torque-summing-member. A counter-balance torque is then commanded by the strain to keep the system in equilibrium.

1.4 Torque Measuring System Features

The desirable features of a good torque measuring system are:

1. Low uncertainty torques
2. A large range of torque
3. Relatively fast response-time
4. Drift-free
5. Dynamically stable
6. Relatively small angular deflection of shaft
7. Excitation insensitive (magnitude and phase)
8. Ease of calibration
9. Ease of reading
10. High resolution
11. Temperature insensitivity
12. Rugged in construction

These requirements are not easy to satisfy concurrently, and for this reason not many good torque meters are commercially available. Those that are on the market are expensive and not very rugged, requiring constant care and maintenance.

In order to optimalize any torque measuring system with respect to the desirable features just mentioned, it now becomes necessary to examine some different modes of the stress-strain balance method. It was mentioned that in this method an elastic deformation was required. In general any conservative stress-strain deformation characteristic is suitable. The general stress-strain functions can be categorized as follows:

1. A constant elastance coefficient (Hooke's Law)
2. A proportional elastance coefficient (The elastance is proportional to the torque)
3. A general variable elastance coefficient (The elastance is adjusted to suit the torque level)

The constant elastance type is the simplest and has many advantages. If the angular deflection or any function thereof is known, the torque stress is known. However, at low torques relative to the magnitude of the elastance, this angular deflection becomes so small as to make any accurate measurement of it quite impossible. Therefore, a constant elastance type is limited by a minimum measurable torque level.

The proportional elastance type where the elastance is proportional to the torque applied results in a constant angular deflection and therefore is not limited in the same manner by a minimum measurable torque level. The low torque limitations will be discussed in more detail later. It does have the advantage of a constant angular deflection of the torque-summing-member.

The general variable elastance coefficient type is a natural choice in that the elastance is arbitrarily chosen to meet whatever standards of performance the particular operator desires. In this report the variable elastance coefficient is an ordered combination of the constant and proportional elastance. It is called the adaptive elastance type by the authors.

CHAPTER 2

THE CONSTANT ELASTANCE METHOD WITH TORQUE GENERATOR SECONDARY CURRENT READOUT

2.1 Electromagnetic Signal and Torque Devices

The Constant Elastance Method is shown schematically in Fig. 2-1 and in block diagram form in Fig. 2-2. In this general method a rigid "frictionless" suspended shaft, called a torque-summing-member, receives as its input, the

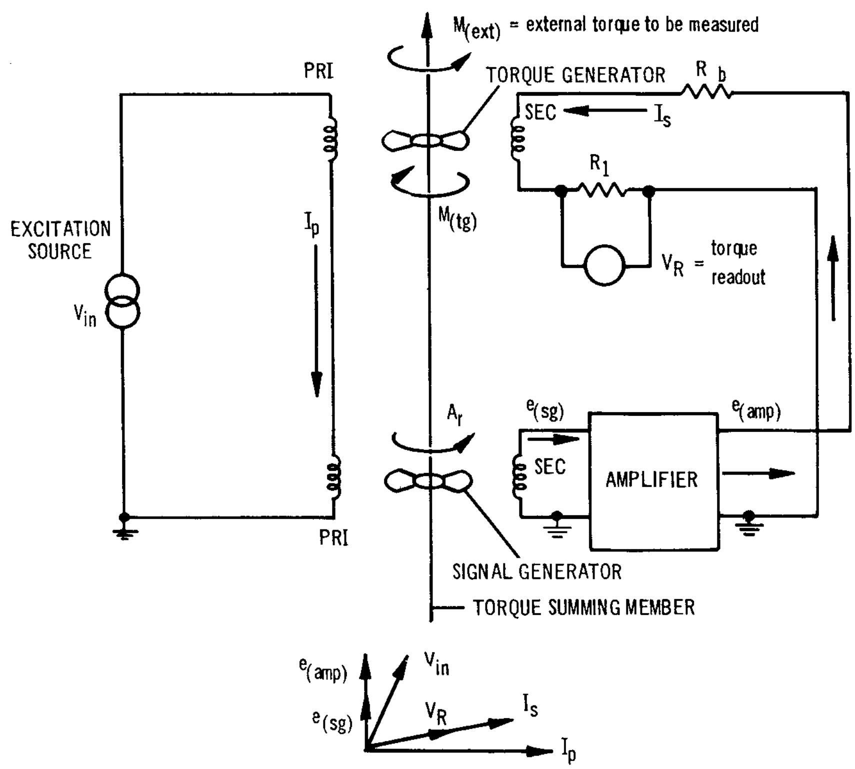


Fig. 2-1. Torque measuring by the constant elastance method, with RMS current readout.

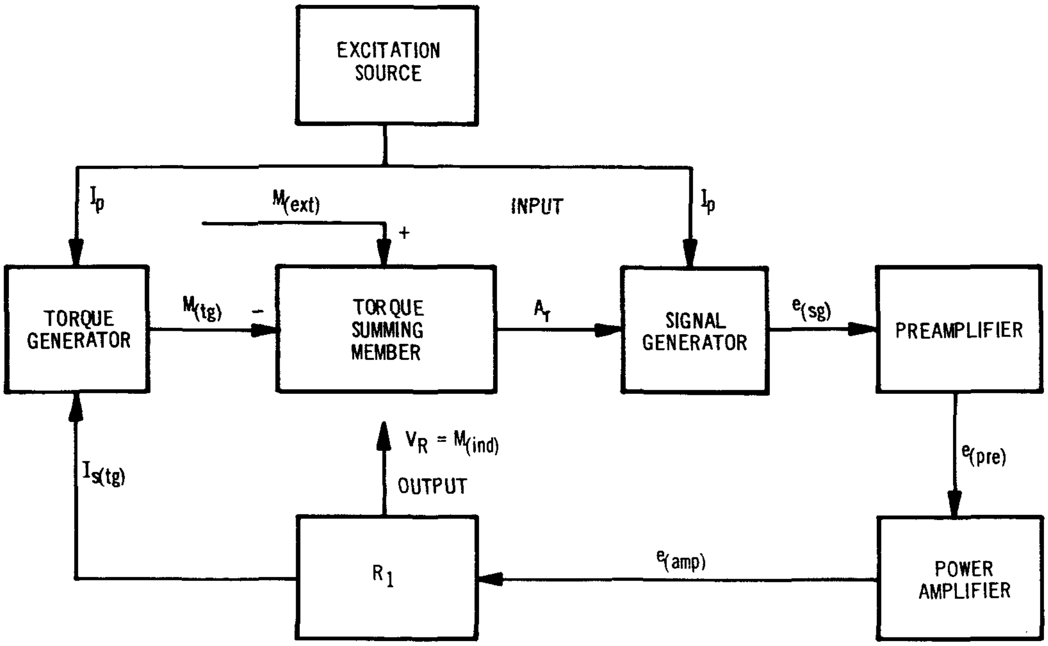


Fig. 2-2. Measuring torque by the constant elastic method with RMS current readout.

external torque to be measured, $M_{(ext)}$. Two similar electromagnetic devices called a microsyn signal generator and torque generator respectively are mounted coaxially about this shaft. The rotors of each are fixed to the rotatable shaft. Their respective stators, with primary and secondary windings, are fixed with respect to the instrument case. As shown in Fig. 2-1, the primaries are connected in series and excited by an alternating current, I_p, from the excitation voltage, V_{in}.

In discussing the simple general constant elastance method no passive circuits to bring about optimum phase relationships are used. This is done purposely in order to make clear the various parameters that can cause deviations in performance in closed-loop torque measurements. In the optimum constant elastance loop, however, methods for improving the precision of the basic loop are discussed in detail.

In the simple loop, actual microsyn performance is treated. This includes quadrature voltage at null, phase shift between excitation and output voltage, and harmonic voltages.

The microsyn signal generator[3] develops an output voltage according to the following relation:

$$e_{(sg)} = S_{(sg)} A_r (\cos \theta_s + j \sin \theta_s) + je_{qs} + |e_{ns}| \qquad (2\text{-}1)$$

where

$e_{(sg)}$ = signal generator output voltage

$S_{(sg)}$ = signal generator sensitivity

A_r = rotor angular deflection from a reference or "null" value

θ_s = phase angle between the output voltage and any arbitrary reference

e_{qs} = signal generator output quadrature voltage

e_{ns} = signal generator output "noise" and harmonics

As will become obvious, the primary current, I_p, is chosen as the basic time-phase reference in this system.

The microsyn torque generator[3] develops an output torque, on the rotor and shaft, according to the following relation:

$$M_{(tg)} = S_{(tg)} I_p (R) I_s \qquad (2\text{-}2)$$

where

$M_{(tg)}$ = moment or torque developed

$S_{(tg)}$ = torque generator sensitivity

I_p = primary current

$(R)I_s$ = Real or in-phase component of the torque generator secondary current, I_s, with respect to the primary current, I_p

2.2 Secondary Current Readout

If the primary current, I_p, is maintained constant, then $(R)I_s$ is a measure of the torque generator torque, and hence the applied external torque

$$(R) I_s = \frac{M_{(tg)}}{S_{(tg)} I_p} = - \frac{M_{(ext)}}{S_{(tg)} I_p} \qquad (2\text{-}2a)$$

The feedback amplifier usually consists of two stages. They are a preamplifier and a power amplifier stage. The preamplifier also acts as a "buffer" between the signal generator output terminals and the power amplifier. This is to prevent signal generator secondary current flow when system compensating voltages

are added to the feedback loop between the preamplifier and the power amplifier stages. The output of the feedback amplifier is given by

$$e_{(amp)} = S_{(amp)}\, e_{(sg)} \tag{2-3}$$

where

$e_{(amp)}$ = amplifier output voltage

$S_{(amp)}$ = amplifier voltage "gain"

$= S_{(amp)\,(pre)}\; S_{(amp)\,(pwr)}$

The current into the torque generator secondary is given by

$$I_s = \frac{e_{(amp)} - e_{(tg)}}{R_1 + Z_{s(tg)} + R_b} \tag{2-4}$$

where

$e_{(tg)}$ = torque generator secondary output voltage or "back-emf"

R_b = torque generator secondary circuit ballast or swamping resistor

R_1 = current sampling resistor

$Z_{s(tg)}$ = torque generator secondary winding input impedance

The purpose of the ballast resistor, R_b, is to make the torque generator secondary circuit impedance appear more constant and resistive. This is because the torque generator secondary winding impedance has some slight nonlinearities because of the iron-core. Also, the torque generator "back-voltage" tends to make the secondary circuit impedance slightly variable.

It must be pointed out that the signal and torque generator are identical devices used for two different functions. Thus a microsyn torque generator with its primary excited develops, in addition to a torque, a secondary output voltage with rotor angular deflection. Similarly a microsyn signal generator develops, in addition to a signal, a torque on its rotor if any component of the secondary current is in-phase with its primary current, I_p. When the torque-summing-member comes to equilibrium, after the external torque to be

measured has been applied, the following is true:

$$M_{(ext)} + M_{(tg)} = 0 \tag{2-5}$$

The dynamics of the torque-to-balance system will not be covered at this point, only the steady-state response will be discussed. Later when the most optimum design is discussed, the dynamic response will be studied.

2.3 Torque Error Due to Signal Generator Quadrature Voltage

The microsyn torque generator output signal or "back-emf" is given by

$$e_{(tg)} = S_{(sg)} A_r (\cos \theta_t + j \sin \theta_t) + je_{qt} + |e_{nt}| \tag{2-6}$$

where

$S_{(sg)}$ = output voltage sensitivity of the microsyn torque generator as a signal generator

θ_t = phase angle between the output voltage and the primary current reference

e_{qt} = torque generator secondary quadrature voltage

e_{nt} = torque generator secondary noise and harmonics

By combining Eqs. (2-1) through (2-6) the external torque becomes

$$M_{(ext)} = - S_{(tg)} I_p S_{(sg)} A_r \left(\frac{S_{(amp)} \; R(\theta_s) - R(\theta_t)}{Z_o^2} \right)$$

$$- S_{(tg)} I_p e_{qs} \left(\frac{S_{(amp)} - \frac{e_{qt}}{e_{qs}}}{Z_o^2} \right) X_o \tag{2-7}$$

Torques due to noise in the torque generator can usually be neglected when there is a pure sinusoidal excitation current.

$$R(\theta_s) = R_o \cos \theta_s + X_o \sin \theta_s$$

$$R(\theta_t) = R_o \cos \theta_t + X_o \sin \theta_t$$

where

R_o = $R_1 + R_{s(tg)} + R_b$ = torque generator secondary circuit resistance

X_o = torque generator secondary circuit reactance

$R_{s(tg)}$ = torque generator secondary winding effective resistance

Z_o = torque generator secondary circuit total impedance
= $R_o + j X_o$

Let the elastance of this simple loop be defined as

$$S_{(fb)} = S_{(tg)} \, I_p \, S_{(sg)} \left(\frac{S_{(amp)} \, R(\theta_s) - R(\theta_t)}{Z_o^2} \right) \tag{2-7a}$$

If the feedback amplifier gain, $S_{(amp)}$, is high enough then $S_{(amp)} \, R(\theta_s) >> R(\theta_t)$, and Eq. (2-7a) reduces to

$$S_{(fb)} = S_{(tg)} \, I_p \, S_{(sg)} \, S_{(amp)} \left(\frac{R(\theta_s)}{Z_o^2} \right) \tag{2-7b}$$

In order to increase the feedback gain, $S_{(fb)}$, the signal generator phase angle, θ_s, between the input and output voltage should be made equal to zero. Since the signal generator and torque generator quadrature voltages are usually of the same order of magnitude, the ratio of e_{qt}/e_{qs} will be nearly unity, and $S_{(amp)} >> (e_{qt}/e_{qs})$. Then Eq. (2-7) becomes

$$\begin{aligned} M_{(ext)} &= - S_{(fb)} \, A_r - \left(\frac{X_o}{R(\theta_s)} \right) S_{(fb)} \left(\frac{e_{qs}}{S_{(sg)}} \right) \\ &= - S_{(fb)} \left[A_r + \left(\frac{X_o}{R(\theta_s)} \right) \left(\frac{e_{qs}}{S_{(sg)}} \right) \right] \end{aligned} \tag{2-8}$$

The real component of the torque generator secondary current, $(R) I_s$, is

$$(R)\, I_s = S_{(sg)} \, S_{(amp)} \left(\frac{R(\theta_s)}{Z_o^2} \right) A_r + S_{(sg)} \, S_{(amp)} \left(\frac{X_o}{Z_o^2} \right) \left(\frac{e_{qs}}{S_{(sg)}} \right) \tag{2-8a}$$

The term $(e_{qs}/S_{(sg)})$ is a fixed angular deviation or deflection because of the signal generator quadrature voltage, e_{qs}. Equation (2-8a) can then be rewritten

$$(R)\, I_s = S_{(sg)} \, S_{(amp)} \left(\frac{R(\theta_s)}{Z_o^2} \right) \left(A_r + (D)\, A_r \right) \tag{2-8b}$$

Where the deviation angle, $(D)\, A_r$ is defined as

$$(D)\, A_r \equiv \left(\frac{X_o}{R(\theta_s)} \right) \left(\frac{e_{qs}}{S_{(sg)}} \right) \tag{2-8c}$$

Equation (2-8) states that the real component of the torque generator secondary current contains two terms. The first term is a true measure of the external torque. The second term in the brackets represents the deviation angle, $(D)\, A_r$, because of the torque arising from the signal generator quadrature voltage, e_{qs}.

$$(D)\, A_r = \left(\frac{X_o}{R(\theta_s)} \right) \left(\frac{e_{qs}}{S_{(sg)}} \right) \tag{2-9}$$

Note that this shift in the torque-summing-member rotational angle, due to the quadrature voltage, e_{qs}, is proportional to the torque generator secondary reactance, X_o. It is inversely proportional to $R(\theta_s)$ and the signal generator sensitivity, $S_{(sg)}$.

The term, $(X_o/R(\theta_s))$, can now be written

$$\frac{X_o}{R(\theta_s)} = \frac{X_o}{R_o \cos\theta_s + X_o \sin\theta_s} \tag{2-9a}$$

The quality factor, Q_o, of the torque generator secondary circuit is defined as

$$Q_o = \frac{X_o}{R_o}$$

Then Eq. (2-9a) may be expressed

$$\frac{X_o}{R(\theta_s)} = \frac{Q_o}{\cos\theta_s + Q_o \sin\theta_s} \tag{2-9b}$$

It is apparent that one way to minimize the deviation angle, (D) A_r, is to make Q_o effectively zero by either increasing the torque generator secondary circuit resistance, R_o, or series tuning the circuit with a capacitor to minimize the circuit reactance, X_o. Increasing R_o makes the circuit look more resistive than reactive.

From Eq. (2-8) it is seen that the quadrature voltage, e_{qs}, results in a torque deviation from the specified torque, $S_{(fb)}\,A_r$.

The torque generator in-phase secondary current component due to e_{qs} to bring about this torque deviation is given by

$$(R)\ I_s = S_{(amp)} \left(\frac{X_o}{Z_o}\right)\left(\frac{e_{qs}}{Z_o}\right) \tag{2-10}$$

The rms quadrature current component through the sampling resistor, R_1, is due to e_{qs}, and neglecting the noise and harmonics, becomes

$$I_s = S_{(amp)} \left(\frac{e_{qs}}{Z_o}\right)\left(\frac{R_o^2 + X_o^2}{Z_o^2}\right)^{1/2} = S_{(amp)} \left(\frac{e_{qs}}{Z_o}\right) \tag{2-11}$$

When $M_{(ext)}$ is not zero, its measurement depends on the magnitude of the primary excitation, I_p, (Ref. Eq. (2-7)) as well as its phase relation. An rms voltmeter used as a readout across the resistor R_1, reads the total current. Therefore, quadrature currents, noise and harmonics will cause deviations in the true readings of torque.

Note that the torque as given in Eq. (2-8) contains two terms. The first term is that component of torque resulting from the signal generator angular

displacement voltage, $S_{(sg)} A_r$. The second term is that component of torque resulting from the signal generator output quadrature voltage, e_{qs}. Note also, that the second term is constant and does not depend on the external torque to be measured. This means that even though the external torque is zero there will be a constant torque due to the signal generator quadrature voltage that must be balanced by the shaft deflecting a certain angle in order to develop an equal and opposite torque.

It is obvious that the signal generator quadrature voltage in the constant elastance loop with no reactance compensation, can cause large deviations in the measurement of true torque as the level of torque approaches zero. Either of two remedies, or both concurrently, are recommended. If in Eq. (2-10), either the quadrature voltage, e_{qs}, or the torque generator secondary circuit reactance, X_o, are made identically zero, this "quadrature" torque vanishes. If both are made equal to zero simultaneously, the rms current readout, $V = I_s R_1$, reads more correctly a measure of the external torque.

2.4 Reduction of Torque Deviations - Optimum Constant Elastance

In order to optimalize the constant elastance loop the following features are recommended, as shown in Fig. 2-3.

1. The microsyn primary circuit be series tuned to resonance by the condenser, C_p, such that the excitation voltage and primary current are in phase.

2. The signal generator secondary be parallel tuned to resonance by the condenser, C_s, such that the signal generator output voltage, $e_{(sg)}$, is in phase with the primary current, I_p.

3. The torque generator secondary circuit be series tuned to resonance by the condenser, C_t, such that the torque generator secondary current, I_s, is in phase with the torque generator primary current, I_p. Note that this not only increases the torque generator efficiency but makes it discriminate against signal generator quadrature voltages.

4. A phase sensitive voltmeter be used for the voltage, V_R, with the reference voltage coming from the excitation voltage. This causes the voltage readout to discriminate against the quadrature current flow in the torque generator secondary circuit. It also tends to discriminate against noise and harmonics if the excitation reference voltage is clean.

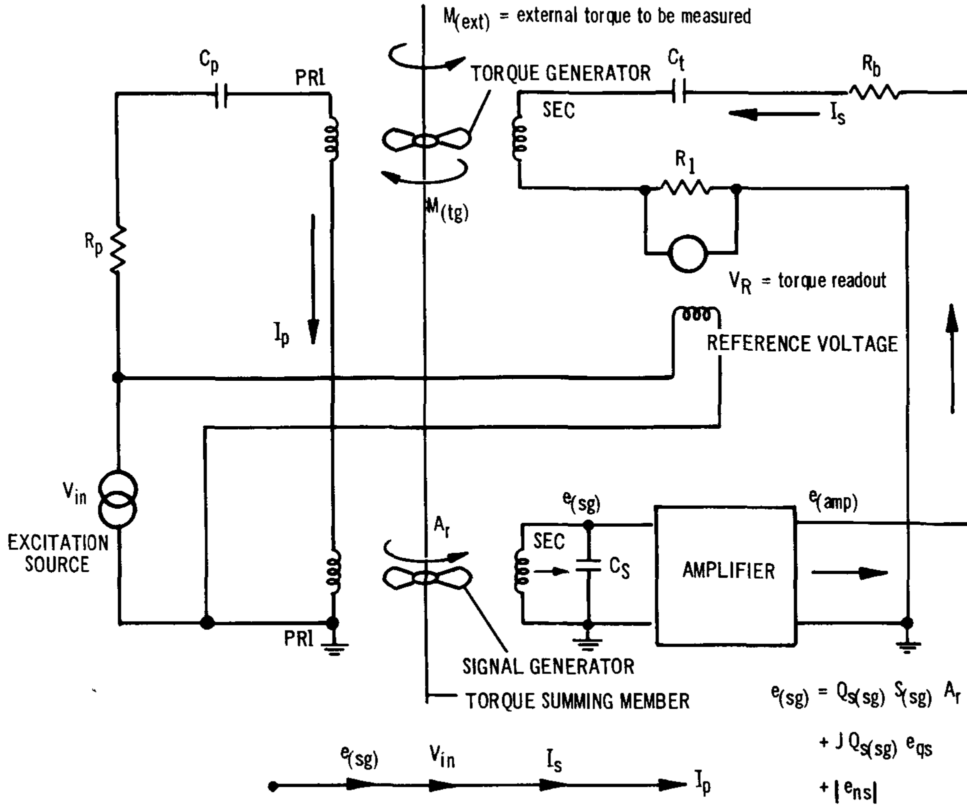


Fig. 2-3. Optimum torque measuring by the constant elastance method, with phase sensitive current readout.

Under these more favorable conditions Eq. (2-7), for the measured external torque, $M_{(ext)}$, becomes:

$$M_{(ext)} = - S_{(tg)} I_p \left(\frac{Q_{s(sg)} S_{(amp)} S_{(sg)}}{R_{s(tg)} + R_1 + R_b} \right) A_r \qquad (2\text{-}12)$$

where

$Q_{s(sg)}$ = quality factor of the signal generator secondary

Note that the resonant capacitor, C_s, on the signal generator secondary increases the sensitivity of the signal output by the quality factor, $Q_{s(sg)}$. This capacitor also tends to reduce the null voltage harmonics and noise.

The elastance of the optimum constant elastance loop is defined as follows:

$$\boxed{S_{(fb)c} = S_{(tg)}\, I_p\, Q_{s(sg)}\, S_{(sg)}\, S_{(amp)} \left(\frac{1}{R_{s(tg)} + R_1 + R_b} \right)} \tag{2-12a}$$

Note that the elastance depends on the following factors:

1. The torque generator sensitivity, $S_{(tg)}$
2. The microsyn primary current, I_p
3. The quality factor, $Q_{s(sg)}$, of the signal generator secondary winding
4. The signal generator sensitivity, $S_{(sg)}$
5. The feedback amplifier gain, $S_{(amp)}$
6. The torque generator secondary circuit resistance, $R_{s(tg)} + R_1 + R_b$

Equation (2-12) can then be simply written

$$M_{(ext)} = - S_{(fb)c}\, A_r \tag{2-12b}$$

There are no variables in the terms making up the loop elastance, $S_{(fb)c}$. In order to increase the overall loop elastance or stiffness, it is mathematically possible to increase any or all the terms in the numerator of Eq. (2-12a) or to decrease any or all the resistances in the denominator. However, in actual practice, only certain terms may be increased or decreased. The torque generator sensitivity, $S_{(tg)}$, may be increased within limits. If it is too high then the torque generator becomes too sensitive to stray secondary currents. Also, its back-voltage, e_{tg}, which is a function of $S_{(tg)}$, can become too high. The primary current, I_p, cannot be safely increased in either microsyn because the reaction or magnetic unbalance torques which are functions of the square of the primary current become excessively high. Also the optimum design of the microsyns dictates the best maximum current to be used. The quality factor, $Q_{s(sg)}$, of the signal generator may also be increased up to a limit. However, if it becomes too high, the signal generator introduces excessive dynamic lag into the feedback circuit and the system becomes unstable at a lower loop elastance. The signal generator sensitivity $S_{(sg)}$, is usually made high. If the feedback amplifier gain, $S_{(amp)}$, is too high, noise and harmonics on the signal generator signal voltage become too high as they are fed back into the torque generator circuit. It is not recommended that the resistance of the torque generator secondary circuit be lowered too much because then the reactive character of the circuit becomes predominant. It has been found that this is inadvisable. The in-phase current as read on the phase-sensitive voltmeter reads

$$V_R = \frac{Q_{s(sg)}\, S_{(amp)}\, S_{(sg)}}{R_{s(tg)} + R_1 + R_b} R_1\, A_r + \delta\, e_n = - \frac{M_{(ext)}\, R_1}{S_{(tg)}\, I_p} + \delta\, e_n \tag{2-13}$$

where

δe_n = a small noise voltage uncertainty or "dead-zone" in the sampling resistor, R_1.

The phase-sensitive voltmeter can be polarized such that both the voltage reading, V_R, and the external torque have the same sign. Then, if noise is neglected

$$\boxed{M_{(ext)} = \left(\frac{S_{(tg)}\, I_p}{R_1} \right) V_R} \tag{2-13a}$$

If it is possible to adjust R_1 such that

$$\frac{S_{(tg)}\, I_p}{R_1} = 1.00$$

then the voltmeter, V_R, reads the external torque directly as

$$M_{(ext)} = V_R \tag{2-13b}$$

In order to measure low torque levels the voltage, V_R, can be amplified with a gain, S_R, when the torque and torque-summing-member deflection angle, A_r, approaches zero. Then Eq. (2-13) becomes

$$S_R\, V_R = S_R\, Q_{s(sg)} \left[\frac{S_{(amp)}\, S_{(sg)}}{R_{s(tg)} + R_1 + R_b} \right] R_1\, A_r + S_R\, \delta e_n \tag{2-14}$$

From Eq. (2-14) it is seen that the lower the torque level and the corresponding deflection, A_r, an increase in voltage readout amplification, $S_R V_R$, only results in a relatively large growth of the "noise" term, $S_R \delta e_n$.

From Eq. (2-13) it is seen that the torque generator secondary current is

$$I_{s(tg)} = -\frac{M_{(ext)}}{S_{(tg)}\, I_p} \tag{2-14a}$$

Therefore, any relationship between this secondary current and the external torque to be measured depends on the constancy of the primary excitation, I_p. This is one of the weak points of the torque generator secondary current readout method.

In summary, the disadvantages of the constant elastance torque measuring system with a torque generator current readout are:

1. The system is excitation current sensitive.
2. There are relatively large torque readout deviations at low torques.

The advantages of this system are:

1. Relative simplicity
2. Uniform response time

CHAPTER 3

THE CONSTANT ELASTANCE METHOD WITH TORQUE GENERATOR PRIMARY AND SECONDARY CURRENT-PRODUCT READOUT

3.1 Excitation Current Magnitude and Phase Insensitivity

In 1958, because of the sensitivity of the current readout system to the magnitude of the primary excitation, Gilinson and Scoppettuolo first used a dynamometer type of wattmeter to readout the torque. See Figs. 3-1 and 3-2. In this scheme the proper current coil is connected in series with the microsyn primaries, and the potential coil is connected in series with the torque generator secondary. The circuits are respectively tuned by condensers as before. The wattmeter reading W, is given as

$$W = S_w I_p (R) I_s \tag{3-1}$$

where

S_W = wattmeter current-product sensitivity.

The relation between the microsyn torque generator output torque and its current product, is

$$M_{(tg)} = S_{(tg)} I_p (R) I_s \tag{2-2}$$

Rewriting Eqs. (3-1) and (2-2) in terms of their respective currents and phase angles gives

$$W = S_w I_p I_s \cos \theta_{ps} \tag{3-2}$$

$$M_{(tg)} = S_{(tg)} I_p I_s \cos \theta_{ps} \tag{3-3}$$

3.2 Scalar Current Product Transfer Concept

The output, W, of the dynamometer represents a scalar current product which provides a torque necessary to deflect the meter-needle against a hair spring. Therefore, the counter-balance scalar current product and torque developed by the microsyn torque generator has been "transferred," as it were, to the wattmeter or current-product meter as a simple means of readout. This is quite different from the former current readout system in which a calibration sensitivity, relating torque units and current units, must be known and maintained. In this current-product transfer method, the readout system obeys the exact same physical law as the microsyn torque generator, but, more

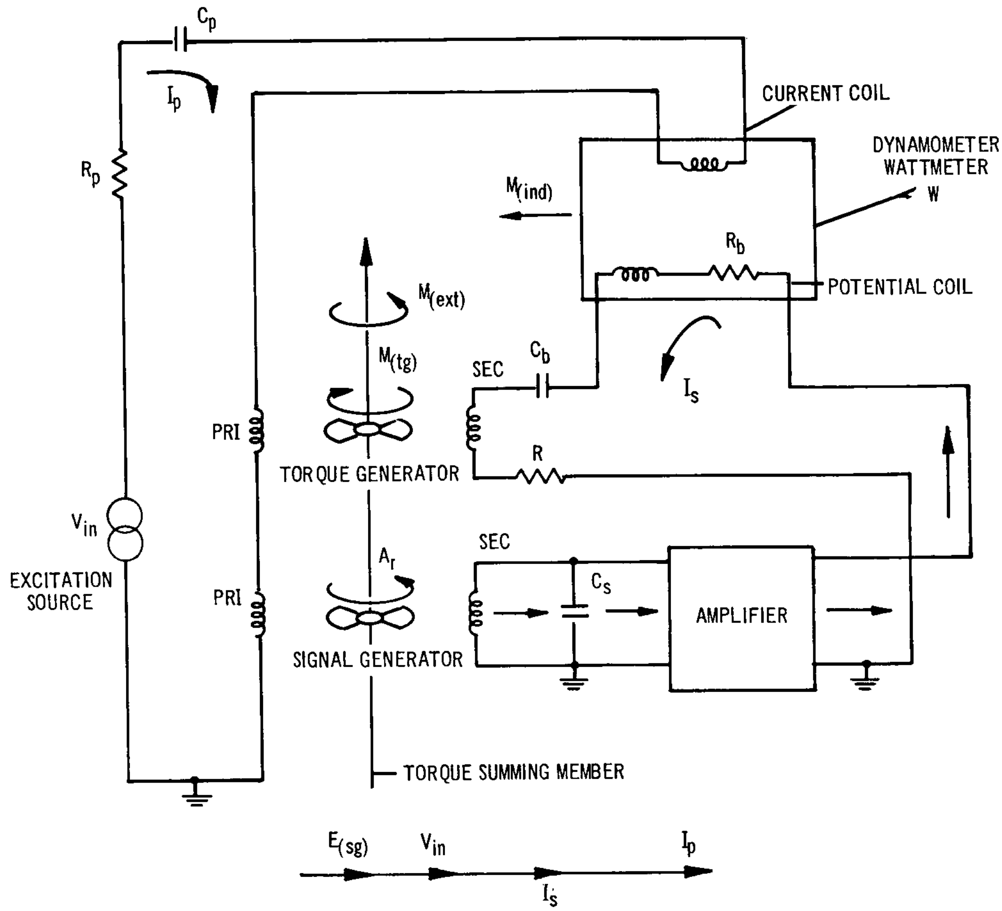


Fig. 3-1. Optimum schematic measuring torque by the constant elastance method, with current-product readout.

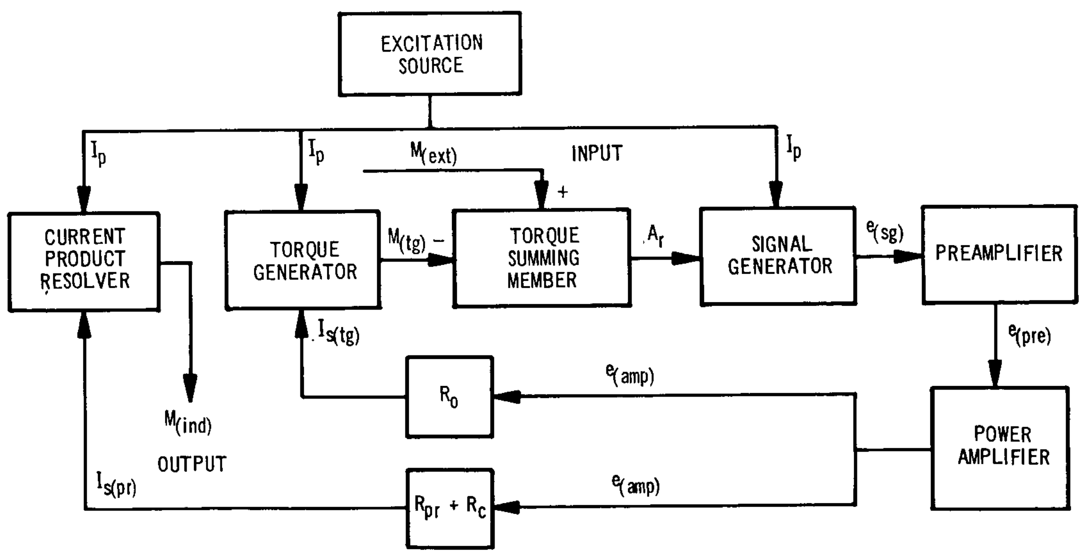


Fig. 3-2. Optimum torque measuring by the constant elastance method with current-product readout.

particularly, it contains three out of four common terms. Dividing Eq. (3-2) by Eq. (3-3) gives

$$\frac{W}{M_{(tg)}} = \frac{S_w}{S_{(tg)}} \tag{3-4}$$

or

$$W = \left(\frac{S_w}{S_{(tg)}}\right) M_{(tg)} = -\left(\frac{S_w}{S_{(tg)}}\right) M_{(ext)} \tag{3-5}$$

Note that by using the torque or current-product transfer method a very simple relationship exists between the torque or current-product of the microsyn torque generator and wattmeter, respectively. No currents, phase angles or impedances are involved in this method of readout. Only the sensitivity ratio of the torque generator and wattmeter is involved. This represents a large step forward in the art of measuring small torques.

Thus, a dynamometer wattmeter scale could be calibrated or marked to read torque directly. Note that this method of measuring torque is excitation magnitude and phase insensitive. Also, since both the microsyn torque generator and the dynamometer type wattmeter obey the same physical law, they are said to "track" one another. In other words, if one device is sensitive to harmonics, quadrature and phase-shifts, so is the other. This tracking feature is one of the principal strong points of the current-product readout system.

From Eq. (3-5), it should be apparent that if the sensitivity of the wattmeter, in watts per milliamperes squared, were equal to the sensitivity of the microsyn torque generator in dyne-centimeters per milliamperes squared, there would be a one-to-one correspondence between the wattmeter reading, W, and the applied torque, $M_{(ext)}$. Thus, in the current product transfer method there is a single-scale torque meter whose calibration does not depend on excitation, phase relations, etc., when used in a constant elastance system. The readout is torque-direction sensitive about a zero-center-reading meter.

This device gives excellent results for a particular full scale value of torque. It is analagous to a single scale meter where accurate readings can be obtained at or near the full scale rating. However, at the low end of the torque scale, the performance naturally deviates from the specification value. One method of increasing the number of ranges is to use various range wattmeters or a multirange wattmeter. But in most cases the switching of different wattmeter circuits with different impedance values may change the calibration of the device.

The advantage of this single-range constant elastance, current product device is its relative low cost. It is particularly applicable to production manufacturers' test facilities where such torques as gyro drift rates and electromagnetic component reaction torques are to be determined. Since in a production facility, these error torques statistically fall within some narrow band of values, a particular full scale reading device can be obtained and used to good advantage.

CHAPTER 4

THE PROPORTIONAL ELASTANCE METHOD WITH TORQUE GENERATOR PRIMARY AND SECONDARY CURRENT-PRODUCT READOUT

4.1 Basic Principles

Although the constant elastance type gives accurate results when using the current-product device, it has the disadvantage of having only one full scale of torque, either, 0-10 dyne-centimeters, 0-25 dyne-cm, 0-100 dyne-cm, etc. In order to develop a multirange torque device, covering many decades of torque level a marked variation was made, as shown in Figs. 4-1 and 4-2. This design uses the method called Proportional Elastance Method, wherein the loop stiffness is proportional to the full-scale torque readout. In this type the feedback transformer accepts its input from the output of the feedback amplifier. This voltage, $e_{(amp)}$, is then proportioned into $(N_B/N_A)\ e_{(amp)}$ volts to the torque generator secondary circuit and into $(N_C/N_A)\ e_{(amp)}$ volts to the secondary circuit of a current-product device with a direct-current zero center readout. The device used can be either a Weston #1483 Product-Resolver or one of many Hall Effect devices (see Fig. 4-3). In the constant elastance system, with a current-product readout, only one full-scale torque can be transferred and read easily. In the proportional elastance system, with a current-product readout, many full-scale torques ranging over many decades can be proportionately transferred to a single current-product meter. This extends the range in which torques can be accurately measured to many decades. Instead of having the torque generator and current-product meter secondaries in series, as they are in the constant elastance method, they are in two parallel circuits fed from the same feedback amplifier output transformer. See Fig. 4-1. These two circuits are hereafter referred to as the torque generator secondary circuit and the current-product resolver secondary circuit, respectively.

4.2 The Attenuator in the Torque Generator Secondary Circuit

In the torque generator secondary circuit there is an attenuator that consists of two major components. See Fig. 4-4. One is the ratio transformer, R_t, with five decade taps and an attenuation, $R = 10^{-4}$, 10^{-3}, 10^{-2}, 10^{-1}, and 1.0. The other, which is connected in cascade, is an autotransformer, or

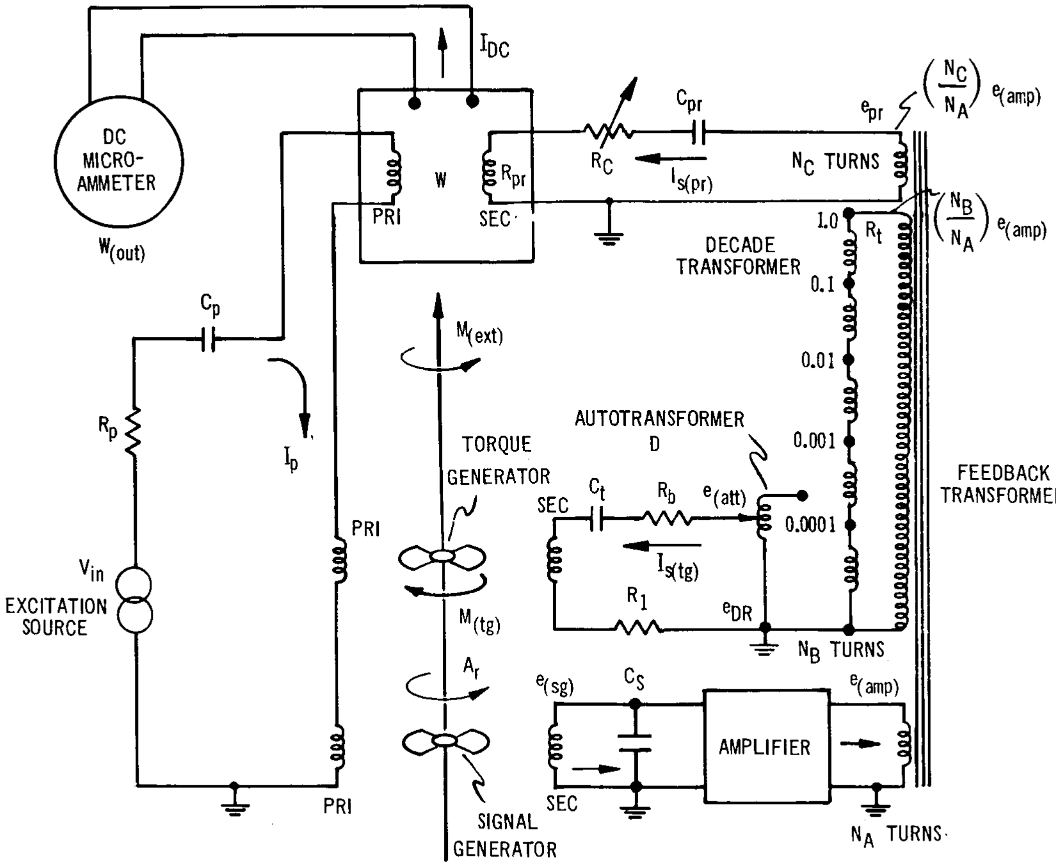


Fig. 4-1. Measuring torque by the proportional elastance method, with current-product readout.

resistive voltage divider D, with a potentiometer-type dial capable of reading its attenuation to five significant figures. For example, $0 \leq D \leq 1.1000$, where $D = 0 \cdot a_1 a_2 a_3 a_4$ and

$$a_1 = 0, 1, 2, 3 \ldots 10$$
$$a_2 = 0, 1, 2, 3 \ldots \ 9$$
$$a_3 = 0, 1, 2, 3 \ldots \ 9$$
$$a_4 = 0, 1, 2, 3 \ldots 10$$

The total attenuation due to these two components in cascade is $0 \leq DR_t \leq 1.1000$.

It is possible by this method to divide the ratio of the torque generator and current-product meter secondary currents into a wide range of values. The advantage of this will become apparent later. Referring to Fig. 4-1, if a given external torque, $M_{(ext)}$, is applied to the torque-summing-member, an angular deflection, A_r, results. This causes the signal generator to generate a signal, $e_{(sg)}$, which when fed into the feedback amplifier, develops a voltage, $e_{(amp)}$, on the feedback transformer winding with N_A turns. There are now developed

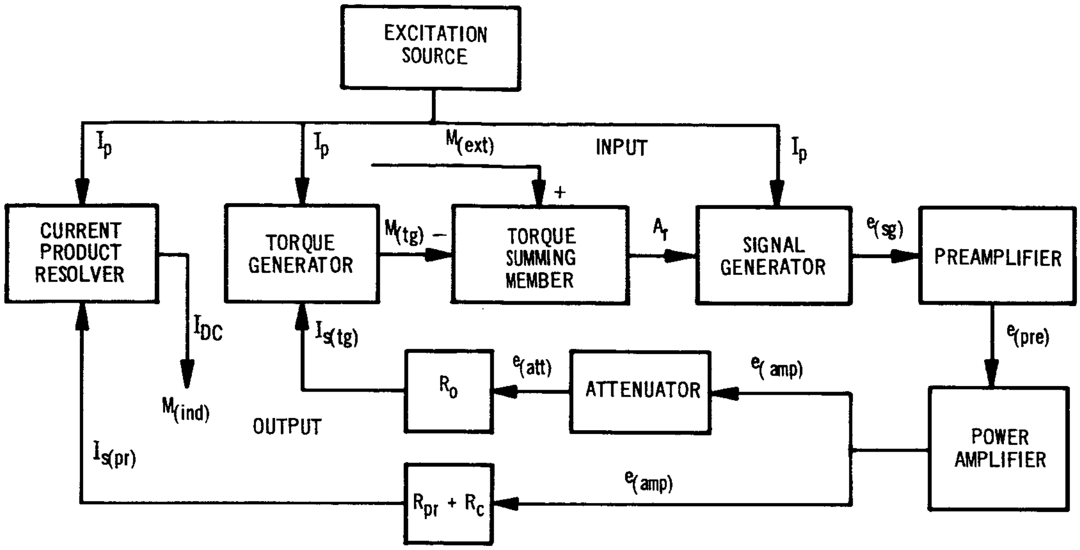


Fig. 4-2. Measuring torque by the proportional elastance method with current-product readout.

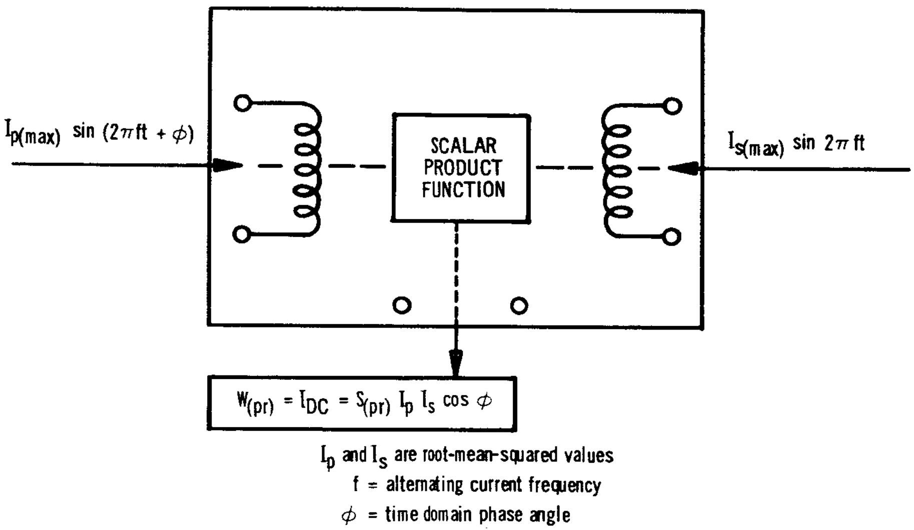


Fig. 4-3. Current-product resolver functional schematic.

voltages of $(N_B/N_A)\ e_{(amp)}$ and $(N_C/N_A)\ e_{(amp)}$ on the torque generator secondary circuit and current-product device secondary circuit N_B and N_C windings, respectively. The voltage after the attenuator, DR_t, is

$$e_{(att)} = DR_t \frac{N_B}{N_A} e_{(amp)} \tag{4-1}$$

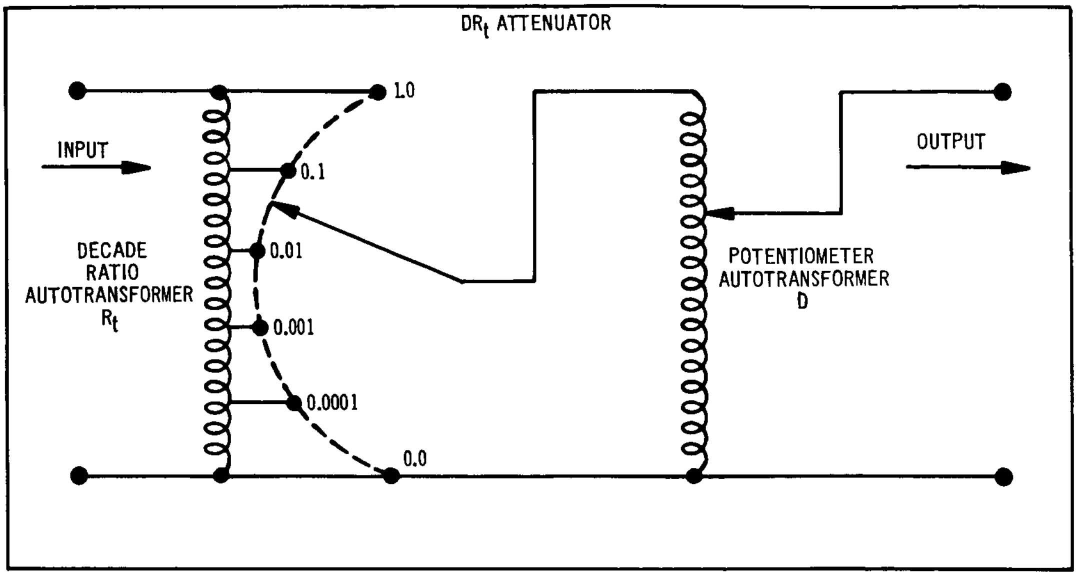


Fig. 4-4. Schematic showing components in the DR$_t$ attenuator.

The voltage into the current-product device secondary is

$$e_{pr} = \left(\frac{N_C}{N_A}\right) e_{(amp)} \tag{4-2}$$

The current into the torque generator secondary, neglecting the torque generator back-voltage, and recalling the series resonant tuned condenser, C_t, which makes $X_o = 0$, is

$$I_{s(tg)} = \frac{e_{(att)}}{R_{s(tg)} + R_1 + R_b} = \frac{DR_t\left(\frac{N_B}{N_A}\right)}{R_{s(tg)} + R_1 + R_b} e_{(amp)} = \left(\frac{N_B}{N_A}\right)\left(\frac{DR_t}{R_o}\right) e_{(amp)} \tag{4-3}$$

The current into the current-product device called a product-resolver is

$$I_{s(pr)} = \frac{e_{pr}}{R_{pr} + R_c} = \frac{\left(\frac{N_C}{N_A}\right)}{R_{pr} + R_c} e_{(amp)} \tag{4-4}$$

where

R_c = calibrating resistor for the torque readout system

Dividing Eq. (4-4) by Eq. (4-3) the product-resolver secondary current becomes, in terms of the torque generator secondary current

$$I_{s(pr)} = \left(\frac{R_{s(tg)} + R_1 + R_b}{R_{(pr)} + R_c}\right)\left(\frac{N_C}{N_B}\right)\left[\frac{1}{DR_t}\right] I_{s(tg)} \tag{4-5}$$

In the constant elastance torque-transfer method, the torque generator and wattmeter secondary currents are equal because their secondary windings are in series. Equation (4-5) shows that by varying DR_t, in the proportional elastance torque-transfer method, a wide range of secondary current ratios, and hence torque ratios, are realized between the torque generator and the product-resolver. From Eq. (4-5) it is seen that the product-resolver secondary current, $I_{s(pr)}$ is not only related to the torque generator secondary current by the usual resistance and transformer-turns ratio, but, more especially, by the reciprocal of the torque generator secondary circuit attenuation factor, (DR_t).

In the steady-state condition, where the applied torque to be measured is equal and opposite to the torque generator developed torque, it follows that

$$M_{(ext)} = - M_{(tg)} = - S_{(tg)}\, I_p\, (R)\, I_{s(tg)} \tag{4-6}$$

Since the secondary torque generator current is in phase with the primary current, by means of the tuned circuits, it then follows that

$$(R)\, I_{s(tg)} = I_{s(tg)} \tag{4-7}$$

4.3 <u>The Direct Current Readout</u>

The product resolver readout is given by a similar equation because its secondary current is also series-tuned to be in phase with the common primary current.

$$W_{pr} = S_{(pr)}\, I_p\, I_{s(pr)} \tag{4-8}$$

where W_{pr} is the direct current output from the current product resolver. Dividing Eq. (4-8) by Eq. (4-6) and combining this result with Eq. (4-5) gives

$$\boxed{W_{pr} = -\left(\frac{R_{s(tg)} + R_1 + R_b}{R_{(pr)} + R_c}\right)\left(\frac{N_C}{N_B}\right)\left(\frac{1}{DR_t}\right)\left(\frac{S_{(pr)}}{S_{(tg)}}\right) M_{(ext)}} \tag{4-9}$$

This gives the relation between the direct current torque readout, W_{pr}, from the product resolver directly in terms of the applied external torque to be measured, $M_{(ext)}$. Note that as the attenuation, DR_t, goes from 1.1000 towards zero, the readout, W_{pr}, increases towards an infinite value for a fixed applied torque $M_{(ext)}$. This means that for very low input torques, it is possible to amplify the readout by simply attenuating the torque generator current correspondingly.

In other words, even though the torque to drive the microsyn torque generator is low, the feedback amplifier is supplying adequate power and torque to drive the current-product resolver at its proper efficiency level where maximum performance is realized. The product-resolver is never obliged to read torque at the low end of its scale where the readout uncertainties are usually large. The attenuator, DR_t, is simply adjusted until the readout, W_{pr}, is high on the output scale. This is one of the major advantages of the proportional elastance current-product transfer method.

4.4 Calibration

The equation for the external torque, $M_{(ext)}$, in terms of the product resolver output is

$$\boxed{M_{(ext)} = -\left(\frac{R_{(pr)} + R_c}{R_o}\right)\left(\frac{N_B}{N_C}\right)\left(\frac{S_{(tg)}}{S_{(pr)}}\right)(DR_t)\, W_{(pr)}} \tag{4-10}$$

The sensitivity ratio, $(SR)_{(tg-pr)}$, of the torque generator to product resolver secondary circuits is defined

$$(SR)_{(tg-pr)} \equiv \left(\frac{R_{(pr)} + R_c}{R_o}\right)\left(\frac{N_B}{N_C}\right)\left(\frac{S_{(tg)}}{S_{(pr)}}\right) \tag{4-11}$$

Then Eq. (4-10) becomes

$$M_{(ext)} = -(SR)_{(tg-pr)}\,(DR_t)\, W_{(pr)} \tag{4-12}$$

Connecting the direct current output meter such that the output, $W_{(pr)}$, and the external torque, $M_{(ext)}$, have the same sign gives

$$\boxed{M_{(ext)} = (SR)_{(tg-pr)}\,(DR_t)\, W_{(pr)}} \tag{4-12a}$$

Since the range of the direct current output is $-1.00 \leq W_{(pr)} \leq +1.00$, it is apparent that if the sensitivity ratio, $(SR)_{(tg-pr)}$, is adjusted such that it is numerically equal to the maximum torque capabilities, $M_{(max)}$, of the instrument, then the following is true at full scale

$$M_{(fs)} = M_{(max)}\,(DR_t) \tag{4-12b}$$

$$M_{(max)} = (SR)_{(tg-pr)} = \left(\frac{R_{(pr)} + R_c}{R_o}\right)\left(\frac{N_B}{N_C}\right)\left(\frac{S_{(tg)}}{S_{(pr)}}\right) \tag{4-12c}$$

Therefore, Eq. (4-12a) can be written

$$M_{(ext)} = M_{(max)}\,(DR_t)\, W_{(pr)} \tag{4-13}$$

and in terms of the full scale torque setting, $M_{(fs)}$

$$\boxed{M_{(ext)} = M_{(fs)}\, W_{(pr)}} \tag{4-13a}$$

Assume a torque measuring instrument with five decades of torque up to a maximum torque capability, $M_{(max)}$, of 1000 dyne-centimeters. This requires a decade transformer such that $R_t = 0.0001$, 0.001, 0.01, 0.1, and 1.0, as shown in Fig. 4-1. With the autotransformer, D, set such that its potentiometer dial setting is $D = 1.0000$, there is a correspondence between decades of torque, M, and the decade taps, R_t, as follows:

FULL SCALE TORQUE $M_{(fs)}$	DECADE TRANSFORMER R_t	POTENTIOMETER AUTOTRANSFORMER D
1000 dyne-cm	1.0000	1.0000
100	0.1000	"
10	0.0100	"
1	0.0010	"
0.1	0.0001	"

Adjust the calibrating resistor, R_c, in Eq. (4-9) until the relationship between the product resolver readout becomes

$$M_{(ext)} = 1000\ DR_t\ W_{(pr)} = M_{(max)}(DR_t)\ W_{(pr)} \tag{4-13b}$$

The negative sign is changed to a positive sign by using the correct polarity of the direct current readout, W_{pr}. With the attenuator, DR_t, set at 1.0000, the relation becomes

$$M_{(ext)} = 1000\ W_{(pr)} = M_{(max)}\ W_{(pr)} \tag{4-13c}$$

The direct current output of the Weston #1483 Product-Resolver is

$$-1.00 \leq W_{(pr)} \leq +1.00 \tag{4-13d}$$

Therefore, the full scale torque for any value of DR_t is, from Eq. (4-13b)

$$M_{(fs)} = \pm 1000\ DR_t = \pm\ M_{(max)}\ DR_t$$

or

$$DR_t = \pm \frac{M_{(fs)}}{1000} = \pm \frac{M_{(fs)}}{M_{(max)}} \tag{4-13e}$$

It can now be seen that to set any full scale torque of 1000 dyne-centimeters or less, for example 50 dyne-centimeters, it is only necessary to set the attenuator at

$$DR_t = 0.050$$

then, by Eq. (4-13e)

$$\begin{aligned} M_{(fs)} &= \pm\ 1000 \times 0.050 \\ &= \pm\ \ 50 \text{ dyne-cm} \end{aligned}$$

Define $$G \equiv 1000\ R_t \equiv M_{(max)}\ R_t$$

then $$1000\ DR_t = GD = M_{(max)}\ DR_t$$

G consists of five push-buttons marked 0.1, 1.0, 10, 100, and 1000 dyne-cm, respectively. Then Eq. (4-13e) becomes

$$GD = \pm M_{(fs)} = \pm M_{(max)}\ DR_t \tag{4-14}$$

Equation (4-14) states that the two-section attenuator, consisting of the decade transformer, R_t, with G = 0.1, 1.0, 10, 100, and 1000, and the potentiometer transformer, D, with $0 \leqq D \leqq 1.1000$, gives a significant figure measure of torque. This is accomplished by adjusting G and D until the product resolver output, $W_{(pr)}$, reads a full scale value of 1.00. For example, assume D and G are adjusted for some unknown external torque such that the direct current output, W_{pr}, reads full scale. Let their respective values be G = 10, and D = 0.2374. With $W_{pr} = 1.00$ the external torque, which is the full scale torque, then becomes by Eq. (4-14)

$$GD = M_{(ext)} = M_{(fs)} = +\ 2.374 \text{ dyne-cm}$$

This means that the attenuator setting, GD, always gives the full scale torque. Therefore, since G has five decade ranges and since D can range from zero to 1.1000 with five significant figures, there are many full scale torque settings available. Even more important is the fact that, if it were possible to expand the full scale reading by some orders of magnitude, the external torque could be accurately measured to four or five significant figures. In other words, for an unknown external torque to be measured, the attenuator, which is in the form of a potentiometer with dials, can be so adjusted that the full scale output, W_{pr}, reads exactly unity. This method will be explained in detail later.

4.5 Proportional Elastance

By combining Eqs. (4-3) and (4-6) the external torque, $M_{(ext)}$, becomes

$$M_{(ext)} = -\ S_{(tg)}\ I_p \left(\frac{Q_{s(sg)}\ S_{(sg)}\ S_{(amp)}}{R_{s(tg)} + R_1 + R_b} \right) \left(\frac{N_B}{N_A} \right) \left((DR_t) \right) A_r \tag{4-15}$$

Where the proportional torque loop elastance, $S_{(fb)p}$, is

$$S_{(fb)p} = S_{(tg)}\ I_p \left(\frac{Q_{s(sg)}\ S_{(sg)}\ S_{(amp)}}{R_{s(tg)} + R_1 + R_b} \right) \left(\frac{N_B}{N_A} \right) DR_t \tag{4-16}$$

Therefore

$$M_{(ext)} = -\ S_{(fb)p}\ A_r \tag{4-17}$$

Note that the torque feedback elastance in the proportional system depends on the following parameters:

1. Torque generator sensitivity, $S_{(tg)}$
2. Primary current, I_p
3. Signal generator sensitivity, $Q_{s(sg)}$ $S_{(sg)}$
4. Torque generator secondary circuit resistance, $R_{s(tg)} \pm R_1 + R_b$
5. Feedback transformer turns-ratio (N_B/N_A)
6. Torque generator circuit attenuation, DR_t
7. Total feedback amplifier gain, $S_{(amp)}$

Comparing Eq. (4-16), which gives the proportional elastance components, with Eq. (2-12a), which gives the constant elastance components, it is noticed that the attenuation factor, DR_t, together with the feedback transformer turns-ratio, (N_B/N_A), are introduced by the proportional elastance system. The turns-ratio term is unimportant except for use in correct impedance matching and is a constant factor.

When discussing the proportional elastance type of torque meter, the important term in this loop elastance is the attenuation term, DR_t. Because the maximum torque level or full-scale reading is equal to the attenuator setting, GD, it follows naturally from Eq. (4-14) that the angular deflection of the torque-summing-member is the same for any full scale torque reading. In other words, no matter what torque range is considered, the range of angular deflection of the torque-summing-member is constant. Equation (4-15) makes this fact self-evident. For if $M_{(fs)} = GD$, Eq. (4-15) becomes

$$\frac{M_{(ext)}}{M_{(fs)}} = -\left[\frac{S_{(fb)p}}{GD}\right] A_r = \frac{A_r}{A_{r(max)}} \tag{4-18}$$

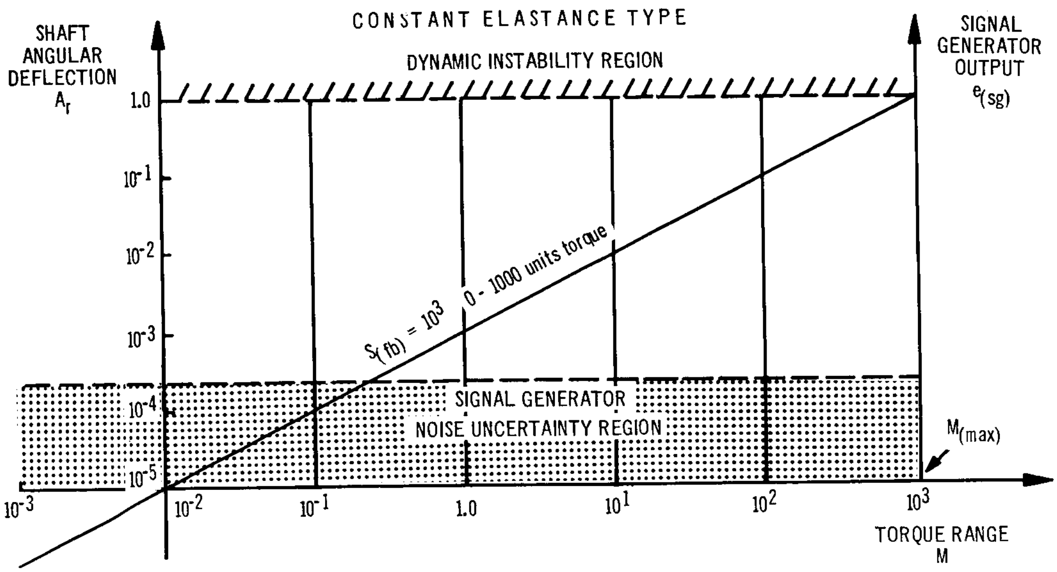
and

$$A_{r(max)} = -\frac{M_{(fs)}}{S_{(fb)p}} = -\frac{GD}{S_{(fb)p}} = \text{constant} \tag{4-19}$$

Therefore, in this system where the loop elastance is proportional to the full scale torque reading, the maximum angular deflection is constant for any torque level.

4.6 Constant vs Proportional Elastance

In the constant elastance system, as is seen from Fig. 4-5, the full-scale angular deflection, signal generator voltage output, amplifier output and readout occur at the maximum torque capability of the instrument.



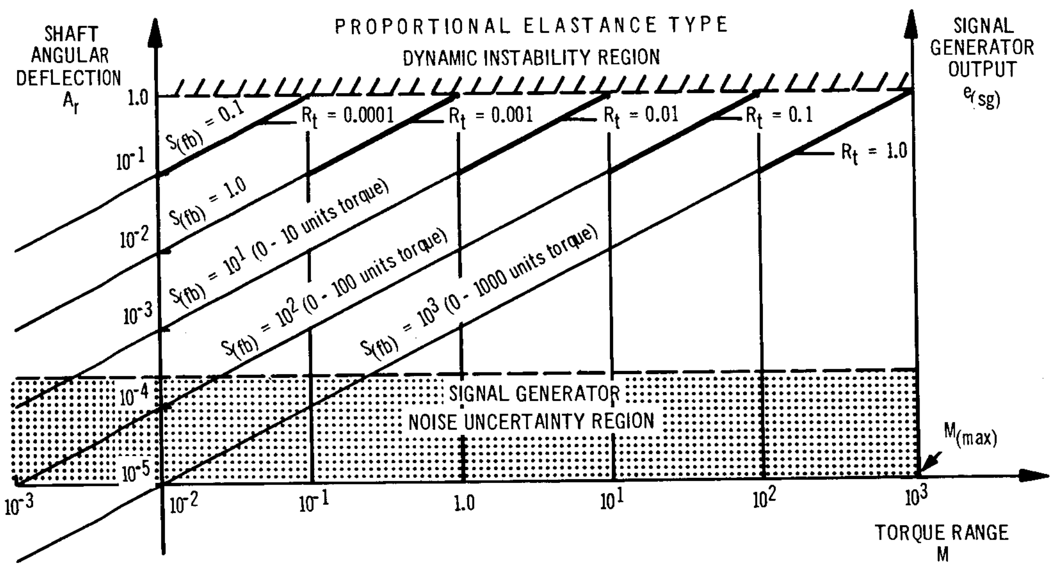


Fig. 4-5. Constant vs. proportional elastance torque systems.

In the proportional elastance system the same full-scale ordinate parameters occur at the five decade ranges of torque. Furthermore, if it were desirable to have any arbitrary full-scale reading of torque, such as 53.85 units of torque, the same full-scale parameters would exist. This means that if the proportional elastance system were always operated at the full-scale readout value, the angular deflection, signal generator output, amplifier output, etc. would always be the same whether 0.0583 or 727.4 units of torque were being measured. Only the torque generator secondary current, fed from the attenuator, varies with torque level. Even the feedback transformer excitation is the same for any value of full-scale torque reading. This is extremely important in that every component in the feedback circuit, with the exception of the torque generator secondary circuit after the attenuator, is operating at the same level of excitation, heating, radiation, etc. This is one of the basic reasons for the precision of this type of torque device.

4.7 Dynamic Response of the Constant and Proportional Elastic Systems

The constant elastance system is operated near the critically damped point, where the damping ratio, $(DR)_{(sys)} = 1$. In this case the equation for the angular deflection is

$$A_r(t) = -\left[\frac{M_{(ext)}}{S_{(fb)}}\right] [1 - (1 + W_n t) e^{-W_n t}] = A_{ro} [1 - (1 + W_n t) e^{-W_n t}] \qquad (4\text{-}20)$$

where

A_{ro} = steady-state angular deflection, $= - M_{(ext)}/S_{(fb)}$

$A_r(t)$ = transient-state angular deflection

W_n = undamped natural frequency of the overall torque loop

In both the constant and the proportional elastance systems, the torque-summing-member is sufficiently damped with a viscous fluid. In the constant elastance case, the amount of damping used provides a damping ratio near unity for an elastance near one dyne-cm per microradian deflection.

$$(DR)_{(sys)} = 1 = \sqrt{\frac{C_d^2}{4S_{(fb)}\, I_{(tsm)}}} \qquad (4\text{-}21)$$

and

$$W_n = \sqrt{\frac{S_{(fb)}}{I_{(tsm)}}} \qquad (4\text{-}22)$$

where

$(DR)_{(sys)}$ = system damping ratio

C_d = damping coefficient of the torque-summing-member

$S_{(fb)}$ = elastance of the system

$I_{(tsm)}$ = moment of inertia of the torque-summing-member about its axis of rotation

This is oversimplified in that it is assumed that all of the dynamic response is concentrated in that of the torque-summing-member. In actual practice this is most certainly true.

In the proportional elastance case the damping ratio is set at unity only at the maximum torque and elastance. It must be realized that as the torque scale is lowered, the loop elastance is lowered due to the attenuator scale change. This means that every torque scale setting below the maximum has a damping ratio greater than unity. In all these cases, the system is said to be overdamped. From Eq. (4-20) it is obvious that the damping ratio increases inversely proportional to the square root of the loop elastance. As the system becomes overdamped it approaches a linear first order system, where its time constant or characteristic time is given as

$$(CT)_{(sys)} = \frac{C_d}{S_{(fb)}} \qquad (4\text{-}23)$$

and the angular response of the torque-summing-member to constant external torque is, in these overdamped cases

$$A_r = -\left(\frac{M_{(ext)}}{S_{(fb)}}\right)\left(1 - e^{-\frac{t}{(CT)_{(sys)}}}\right) \qquad (4\text{-}24)$$

4.8 Characteristic Time

From Eq. (4-23) it can be noticed that as the torque scale and the corresponding torque elastance are lowered the "characteristic time," $(CT)_{(sys)}$, or "response time" increases in proportion. This effect is quite advantageous in that there is an automatic adaptive "filter" such that as the torque to be measured gets lower where external disturbing oscillatory torque amplitudes become relatively higher, they are filtered out to an increasing degree. However, there is a price to pay for this filtering. Since the proportional elastance system allows torque to be measured over many decades, or orders of magnitude, the characteristic time increases by an order of magnitude for every decrease in torque scale order of magnitude. Table 4-1 gives some sample elastances and characteristic times for various full-scale torque levels used.

Table 4-1. Typical parameters for a proportionate elastance system.

TORQUE LEVEL $M_{(fs)}$ dyne-cm	ELASTANCE $S_{(fb)p}$ (dc/mr)	CHARACTERISTIC TIME $(CT)_{(sys)}$ (seconds)
1000	1000	
100	100	0.02
10	10	0.15
1	1	1.5
0.1	0.1	15.0
0.01	0.01	150.0

It can be seen that to measure torques down to a level of 0.010 dyne-centimeters, the response time becomes prohibitively long. One alternative is to increase the loop elastance proportionately for all orders of magnitude of torque. However, in the practical system, dynamic instability sets in at the higher torque levels and elastances unless stability compensation is added.

4.9 Lead Network

It was therefore necessary to introduce some dynamic compensation in the form of a lead-network. This is done by adding a parallel lead-type circuit to the feedback amplifier circuit, as shown in Fig. 4-6. The elastance can then be increased by an order of magnitude as shown in Table 4-2.

Table 4-2. Typical parameters for a proportionate elastance system with rate stabilization.

TORQUE LEVEL (dyne-cm)	ELASTANCE $S_{(fb)p}$	CHARACTERISTIC TIME (seconds)
1000	10,000	
100	1000	
10	100	0.02
1	10	0.15
0.1	1	1.5
0.01	0.1	15.0

It is then possible to measure torque at the 0.01 dyne-cm level with a characteristic time of no more than 15 seconds. However, in the field of aerospace technology, where this type of instrument is used to measure gyroscope and accelerometer drifts to such low torque levels (0.0001 to 0.001 dyne-cm), the characteristic time again becomes prohibitively large. A general variable

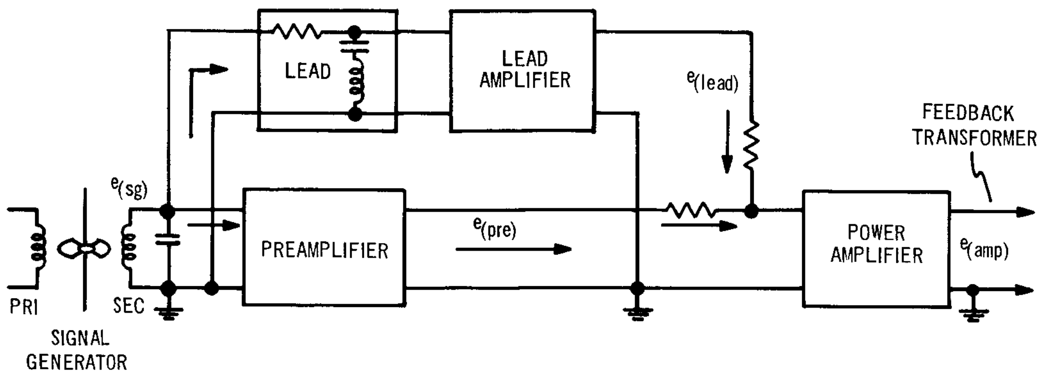


Fig. 4-6. A method for obtaining rate stabilization in an a-c system.

elastance coefficient might be advantageous to use under these conditions. Then the response time at low torque levels might be decreased at the discretion of the operator. A gain-control can be manually adjusted to provide the proper elastance and response time at the particular level of torque that is desired. This method is unwieldy and introduces transients into the electronic feedback system that sometimes destroy the very precision for which the device was designed.

This is particularly true in the field of low viscosity-low shear rate viscometry, where this instrument finds a useful application. In the low shear-rate regions of certain non-Newtonian fluids,[4][5] small changes in viscous torque must be measured. Any electrical disturbance of the feedback loop may completely invalidate these small torque readings. This is also true in the measurement of the so-called "yield value"[6] of certain solutions, such as blood, paints, etc. The yield value may be defined as that shear stress that occurs between the boundary surfaces of a liquid and a smooth hard surface in shear when the shear rate between them approaches zero. This phenomenon is a function of the solid particles in suspension and their related friction to the moving shear surface. Any sharp rate of change of the slowly approaching zero shear rate destroys the molecular bond between the particles and the moving boundary surface.

CHAPTER 5

THE ADAPTIVE ELASTANCE METHOD WITH TORQUE GENERATOR PRIMARY AND SECONDARY CURRENT-PRODUCT READOUT

5.1 Torque Range Limits

A method of adaptive elastance control was designed that utilized the best advantages of both the constant elastance and the proportional elastance systems. This Adaptive Elastance Method can be more clearly understood by referring to Fig. 5-1, which is a diagram of the elastance and torque scale plotted in orders of magnitude. It should be noted that in a torque measuring system there are constraints or limits entirely surrounding the parameters on a Cartesian plot of elastance vs torque level. Figure 5-2 shows a simplified plot further indicating the limits surrounding the useful torque measurement area. As can be seen, the constant elastance system has the smallest torque range but has the fastest response time. Note that the proportional elastance system has a larger torque range but a longer response time at low torque levels. Also note that the adaptive elastance system has the largest torque range and borrows the best from the other two systems.

5.2 Adaptive Feedback

The adaptive elastance is actually implemented, by a current-feedback of the microsyn torque generator current in a negative sense, into the feedback amplifier as shown in Figs. 5-3 and 5-4. Since the torque generator secondary current, $I_{s(tg)}$, is proportional to the torque level, the algebraic sum of the preamplifier voltage, $e_{(pre)}$, and the negative feedback voltage, $e_{(fb)}$, result in an adaptive elastance, as shown in Fig. 5-2. Remember that with proportional elastance control, the preamplifier output, $e_{(pre)}$, is constant for any full scale torque reading. However, at high torque levels the over-all gain of the total amplifier stage, preamplifier plus power amplifier, is small with the adaptive elastance method. This is because of the negative feedback, where the input-output relations are:

$$e_{(pre)} - e_{(fb)} = e_{(pre)} - S_{(ad)}\, I_{s(tg)}\, R_1 \qquad (5\text{-}1)$$

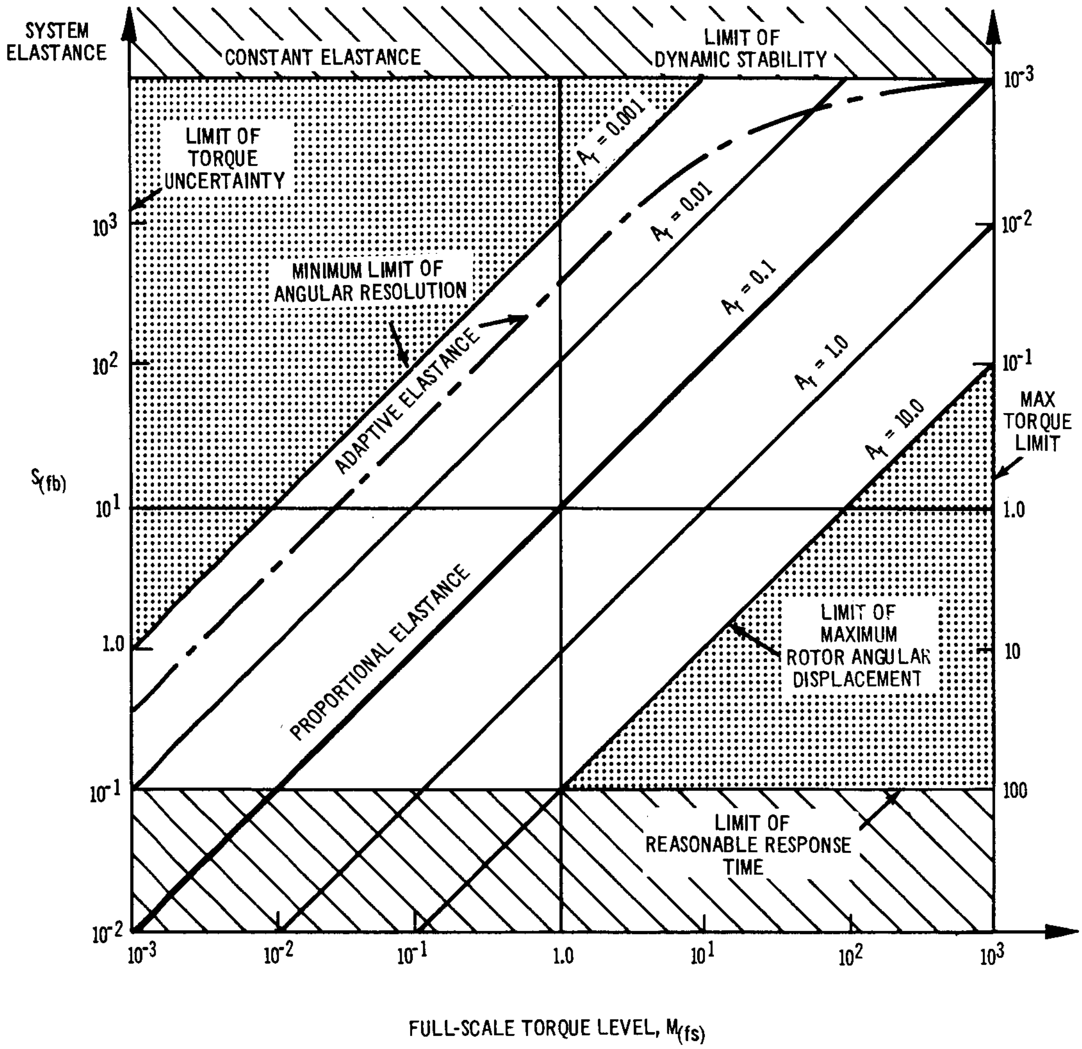


Fig. 5-1. Adaptive elastance as a compromise between constant and proportional elastance.

and the external torque is (in the steady state)

$$M_{(ext)} = -\frac{S_{(tg)}\, I_p}{R_o}\left[\frac{DR_t\left(\frac{N_B}{N_A}\right) G_{s(sg)}\, S_{(sg)}\, S_{(pre)}\, S_{(amp)}}{1 + S_{(ad)}\, S_{(amp)}\, DR_t\left(\frac{N_B}{N_A}\right)\left(\frac{R_1}{R_o}\right)}\right] \qquad (5\text{-}2)$$

where

R_1 = feedback sampling resistor

R_b = torque generator secondary circuit ballast resistor

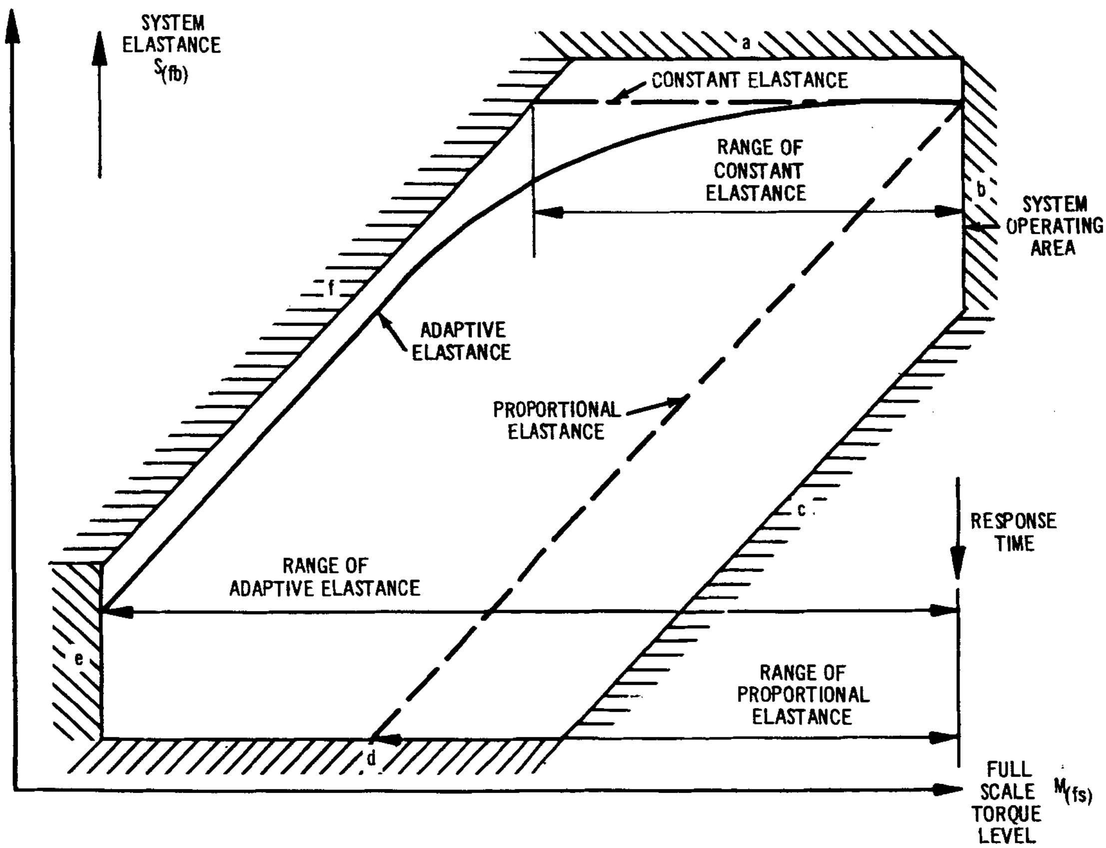
$R_{s(tg)}$ = torque generator secondary resistance

$S_{(ad)}$ = adaptive feedback sensitivity

$S_{(pre)}$ = preamplifier sensitivity

$S_{(amp)}$ = power amplifier sensitivity

R_o = $R_1 + R_b + R_{s(tg)}$ = total torque generator secondary circuit resistance



a – LIMIT OF DYNAMIC STABILITY
b – LIMIT OF MAXIMUM TORQUE
c – LIMIT OF ANGULAR DISPLACEMENT
d – LIMIT OF REASONABLE RESPONSE TIME
e – LIMIT OF TORQUE UNCERTAINTY
f – LIMIT OF ANGULAR RESOLUTION

Fig. 5-2. Constraints on the torque-to-balance measuring system.

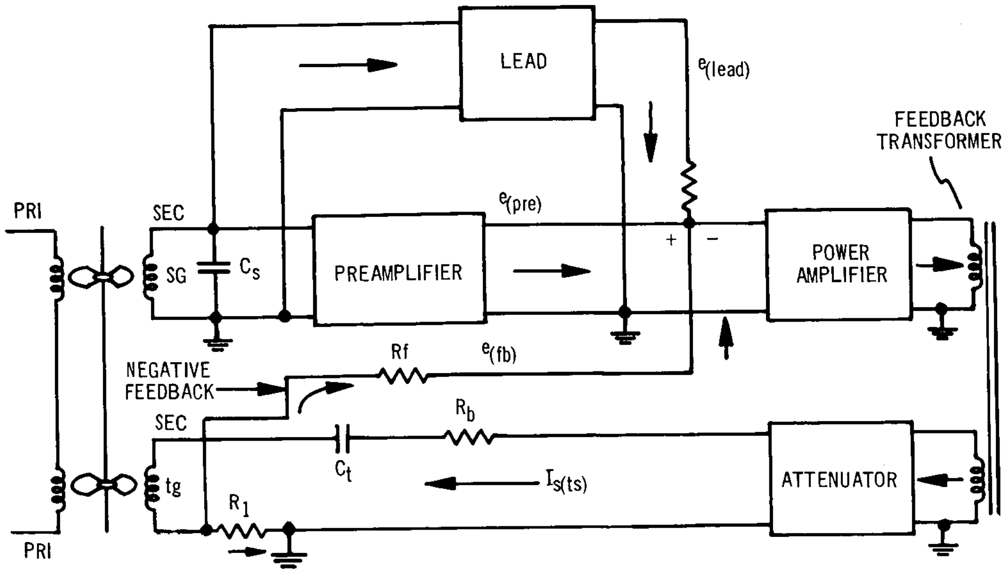


Fig. 5-3. Negative current feedback for adaptive elastance control.

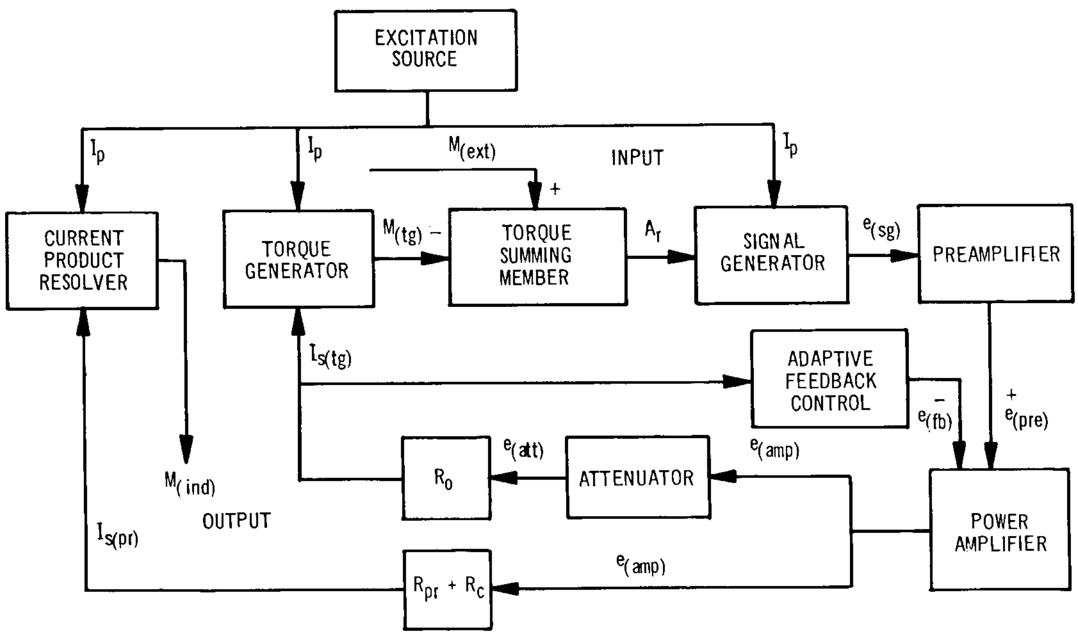


Fig. 5-4. Negative current feedback for adaptive elastance system.

The elastance of the adaptive elastance loop is defined as

$$S_{(fb)a} = \frac{S_{(tg)}\, I_p}{R_o} \left[\frac{Q_{s(sg)}\, S_{(sg)}\, S_{(amp)fb}}{1 + S_{(ad)}\, S_{(amp)} \left(\frac{N_B}{N_A}\right) DR_t \left(\frac{R_1}{R_o}\right)} \right] \left(\frac{N_B}{N_A}\right) DR_t \tag{5-3a}$$

where

$S_{(amp)fb}$ = total feedback amplifier gain

= $S_{(pre)}\, S_{(amp)}$

Rewriting Eq. (4-16) for the proportional elastance loop, it follows that

$$S_{(fb)p} = \frac{S_{(tg)}\, I_p}{R_o} \left(Q_{s(sg)}\, S_{(sg)}\, S_{(amp)fb}\right) \left(\frac{N_B}{N_A}\right) DR_t \tag{5-3b}$$

Rewriting Eq. (2-12a) for the constant elastance loop it follows that

$$S_{(fb)c} = \frac{S_{(tg)}\, I_p}{R_o} \left(Q_{s(sg)}\, S_{(sg)}\, S_{(amp)fb}\right) \tag{5-3c}$$

Note, from Eq. (5-3a), that as the torque-level increases (and also DR_t) the loop-elastance or "stiffness" tends to "level-off" rather than increase in proportion. Figure 5-5 shows a plot of elastance vs torque level for the three methods.

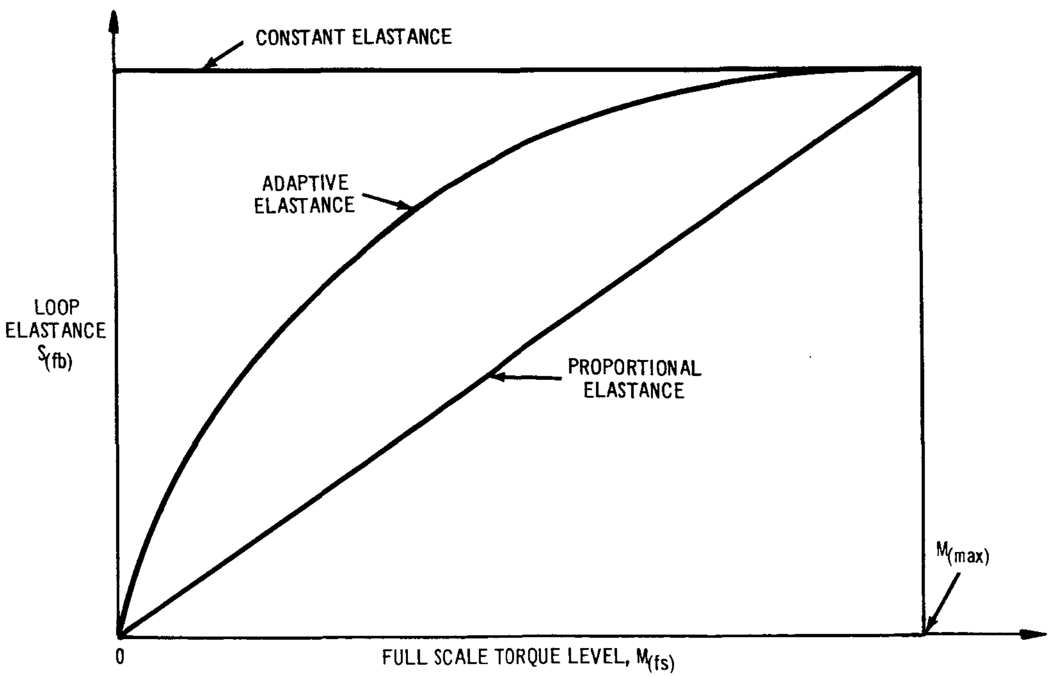


Fig. 5-5. Loop elastance vs. torque level for the three types of instruments.

5.3 Response Time Compromise

The relation of the applied torque and the torque-summing-member deflection angle, A_r, is shown in Fig. 5-6. Note how limited the constant elastance torque range is as compared to the proportional and adaptive elastance torque ranges. Figure 5-7 illustrates how the characteristic time, or response-time affects the three modes of elastance. The figure shows a plot of the system characteristic time $(CT)_{(sys)}$ as a function of the full scale torque setting. Note

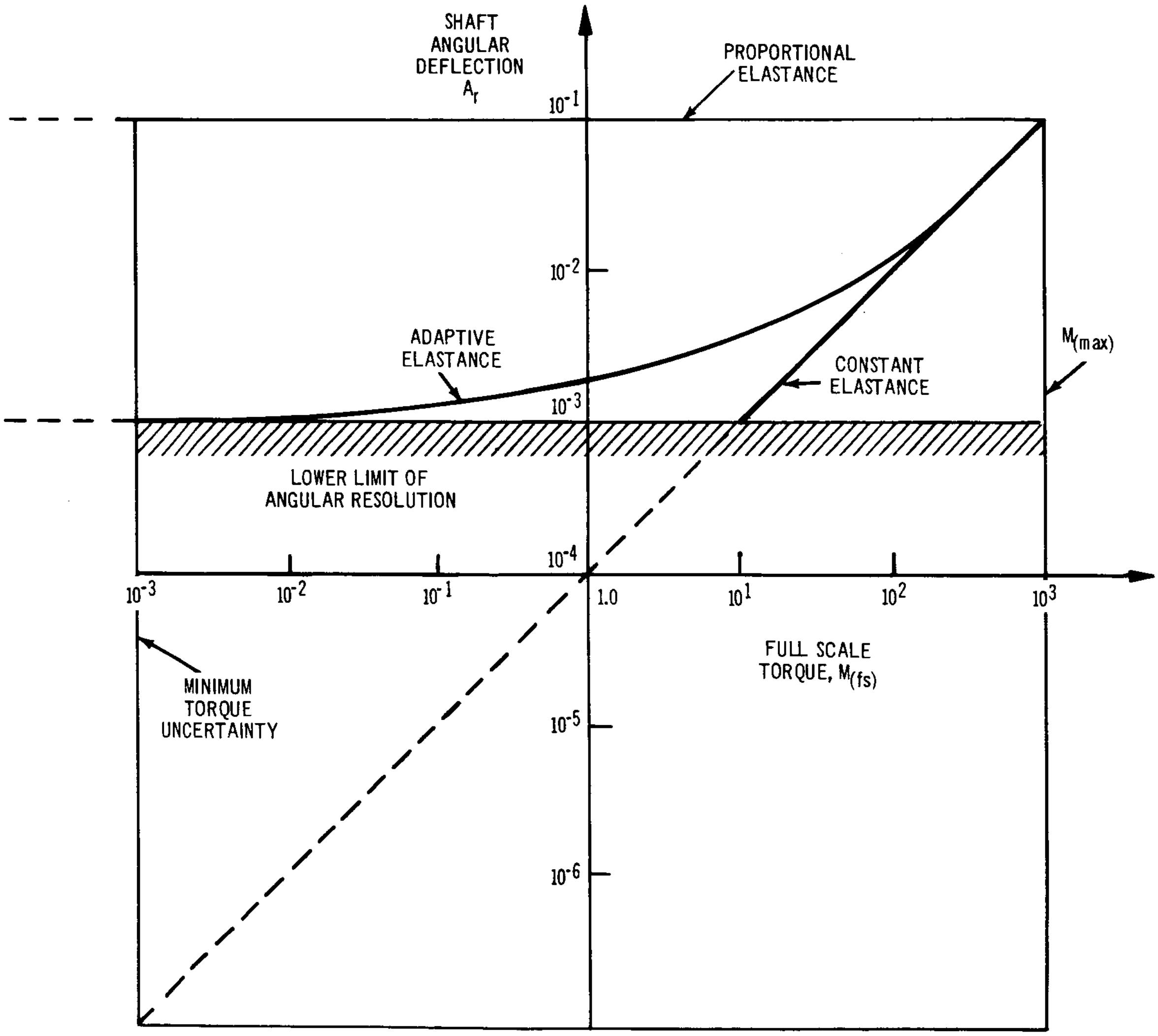


Fig. 5-6. Torque-angular deflection for various types of elastance.

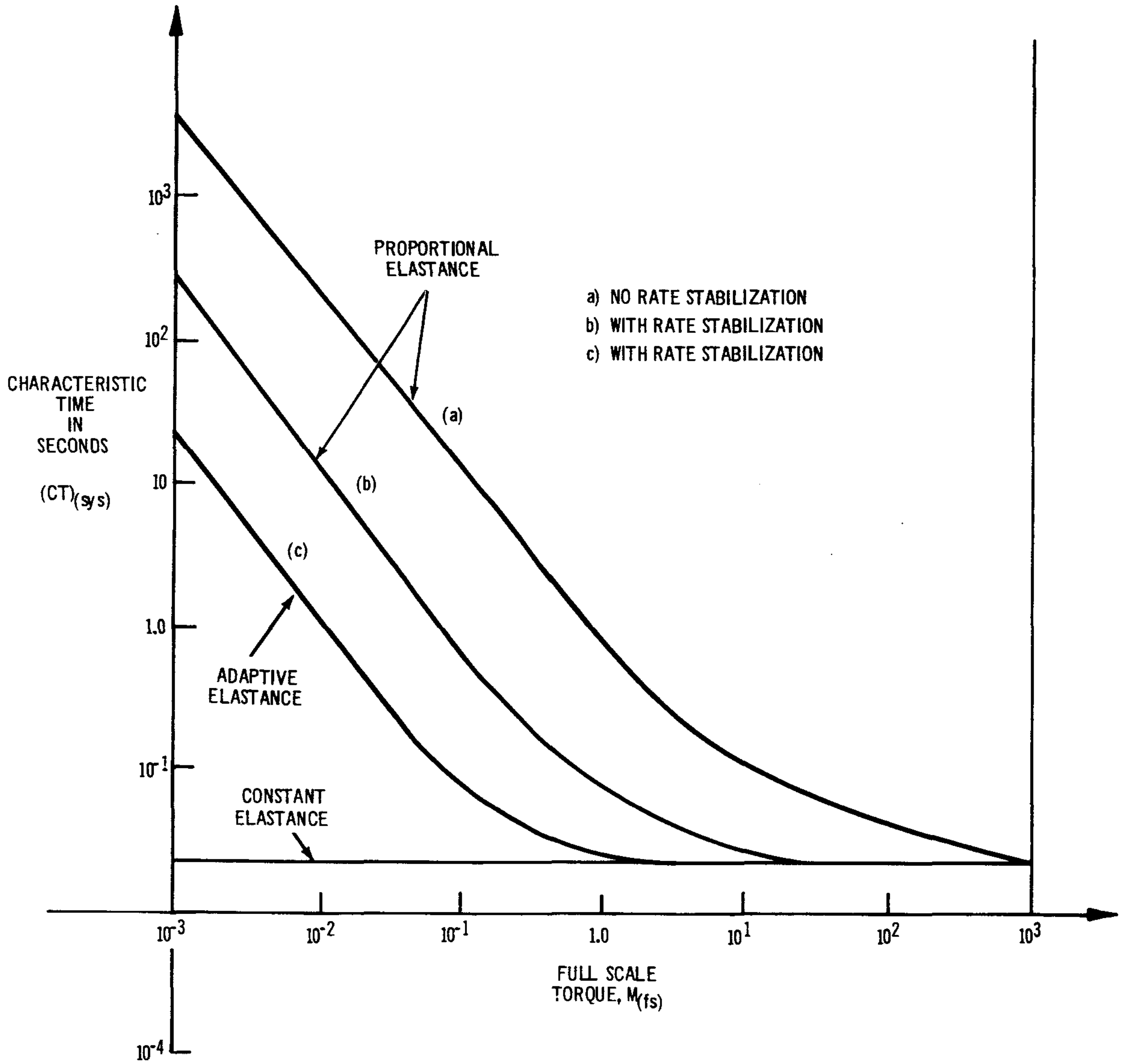


Fig. 5-7. System characteristic time for various types of elastance.

that the rate stabilization circuit allows a "speed-up" of the response time. The speed of response of direct current meter readout is included in the definition of the system characteristic time. This is the reason that the proportional elastance curve deviates from a straight line for high torque scale settings. The adaptive elastance method keeps the response, at low torque levels, within due bounds of

time. It is felt that the adaptive elastance control, together with the proper rate-stabilization, results in a torque-measuring system as satisfactory as any previously devised. It utilizes the advantageous parameters of the constant elastance system at high full scale torque settings, where uncertainty torque effects are relatively low, and includes the advantageous parameters of the proportional elastance system at very low full scale torque settings. It is analogous to the design of a wide frequency band high-fidelity amplifier, where excellent performance at both high and low frequencies is maintained by the proper exploitation of the good features at both ends of the frequency band. Table 5-1 shows the typical parameters associated with the Adaptive Elastance Method.

Table 5-1. Typical parameters for an adaptive elastance system with rate stabilization.

TORQUE LEVEL (dyne-cm)	ELASTANCE $S_{(fb)p}$ (dc/mr)	CHARACTERISTIC TIME $(CT)_{(sys)}$ (seconds)
1000	10,000	
100	5,400	
10	930	
1	100	0.02
0.1	10	0.15
0.01	1	1.5

Notice how the response time at the low torque levels is materially reduced through the use of the adaptive system. In this system the elastance at the 1000 dyne-cm level is usually set between 2000 and 10, 000 dyne-cm per milliradian.

CHAPTER 6

ERROR COMPENSATIONS

6.1 Basic Error Sources

In the actual complete instrument there are signal and torque errors which must be compensated for in order to fully realize the optimum capabilities of the instrument. They are as follows:

1. Signal and torque generator reaction torque
2. Signal generator quadrature and harmonic voltage at null
3. Torque generator quadrature and harmonic voltage at null
4. Signal and torque generator null voltage angular misalignment
5. Torque generator secondary voltage with rotor angular displacement
6. Attenuator leakage impedance
7. Core hysteresis effects
8. Base motion effects

The series resonance tuning of the excitation circuit, the parallel resonance tuning of the signal generator primary, and the series resonance tuning of both the torque generator secondary and the current-product resolver secondary have been briefly mentioned earlier but since they are, in fact, phase compensators they will be discussed here. By proper tuning and the use of nonphase-shift components in the feedback loop, it is possible to keep both the torque generator and the product resolver secondary currents in phase with their common primary excitation current. One advantage in using resonant circuits is that changes in circuit resistance due to internal or external heating are phase insensitive. An advantage in parallel tuning the signal generator secondary winding (in addition to its phasing) is that it increases the output sensitivity by the quality factor, $Q_{s(sg)}$, of the secondary, while decreasing the harmonics and noise in the output signal voltage. A disadvantage is that any change in quadrature voltage on the signal generator secondary terminals results in a secondary current component in phase with the primary current, and therefore, a change in unbalance magnetic torque results.

This is evident by a drift in the direct current meter away from zero in the torque readout. Figure 6-1 shows an overall time-phase diagram of the important currents and voltages in the torque measuring system. The following is a list of these voltages and currents:

V_{in} = excitation voltage

I_p = common primary current to both microsyns and the current product resolver

$e_{(sg)}$ = signal generator output voltage

$e_{(tg)}$ = torque generator "back" voltage

$e_{(amp)fb}$ = total feedback amplifier voltage

$e_{(att)}$ = attenuator output voltage

$e_{(pr)}$ = product resolver input voltage

$I_{s(tg)}$ = torque generator secondary current

$I_{s(pr)}$ = product resolver secondary current

I_{qs} = signal generator secondary current due to its own quadrature voltage across the secondary capacitor

If there is any slight phase shift between the signal generator output and the feedback transformer, a small trimming lead or lag RC network can be inserted between the preamplifier and the power amplifier.

6.2 Signal and Torque Generator Reaction Torque

It will be pointed out in the next chapter that in a well designed and possibly a compensated "air-bearing" support, no unbalance autorotational torque will exist. This assumes a well-balanced device both from the air-flow conditions as well as from the vertical mounting of the torque summing member in the earth's gravitational field. However, there will exist in general a torque reading on the readout meter even with no applied external torque. This is a magnetic reaction torque due to both signal and torque generators, proportional to the square of their primary excitation. It is because of core and coil assymetries and represents a difference of adjacent stator-pole torques pulling in opposite directions.

In general this reaction torque is considered in two components:

1. A fixed torque at the zero or null voltage position
2. An elastic torque with rotor angular displacement

Figure 6-2 shows the reaction torque both before and after compensation. It can be demonstrated that since the signal generator output voltage causes a current

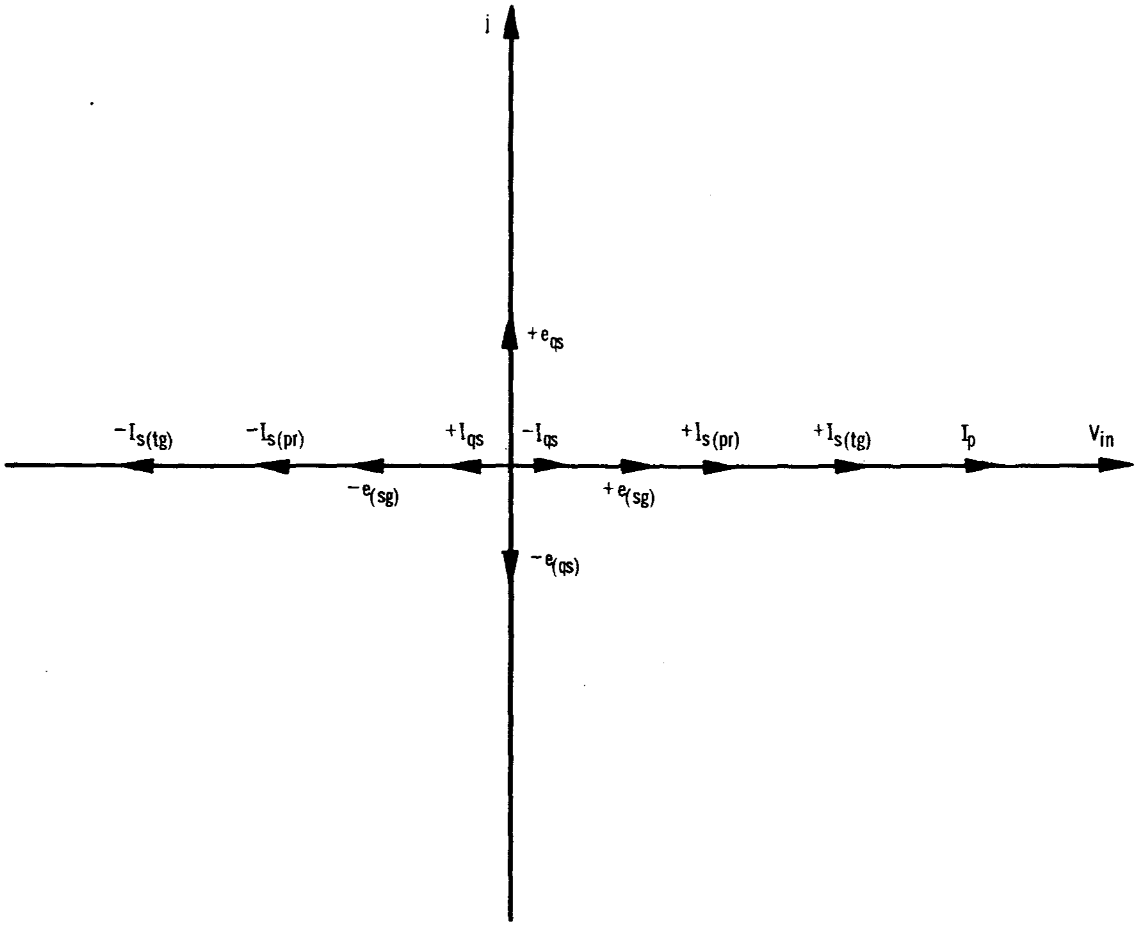


Fig. 6-1. Phase diagram of voltage and currents in the adaptive elastance control system.

to flow in the resonant secondary capacitor which is 90° out of phase with the primary current (see Fig. 6-1) no elastic torque from this current results. Hence, the elastic restraint torque of the signal and torque generator are equal and add algebraically. In general the reaction torque is expressed as follows:

$$M_{(react)} = M_o - S_r A_r$$
$$= \text{fixed term} + \text{elastic term} \qquad (6-1)$$

where

$M_{(react)}$ = signal and torque generator total reaction torque

M_o = signal and torque generator total torque at zero angle

S_r = elastic restraint sensitivity

A_r = rotor angular displacement from null

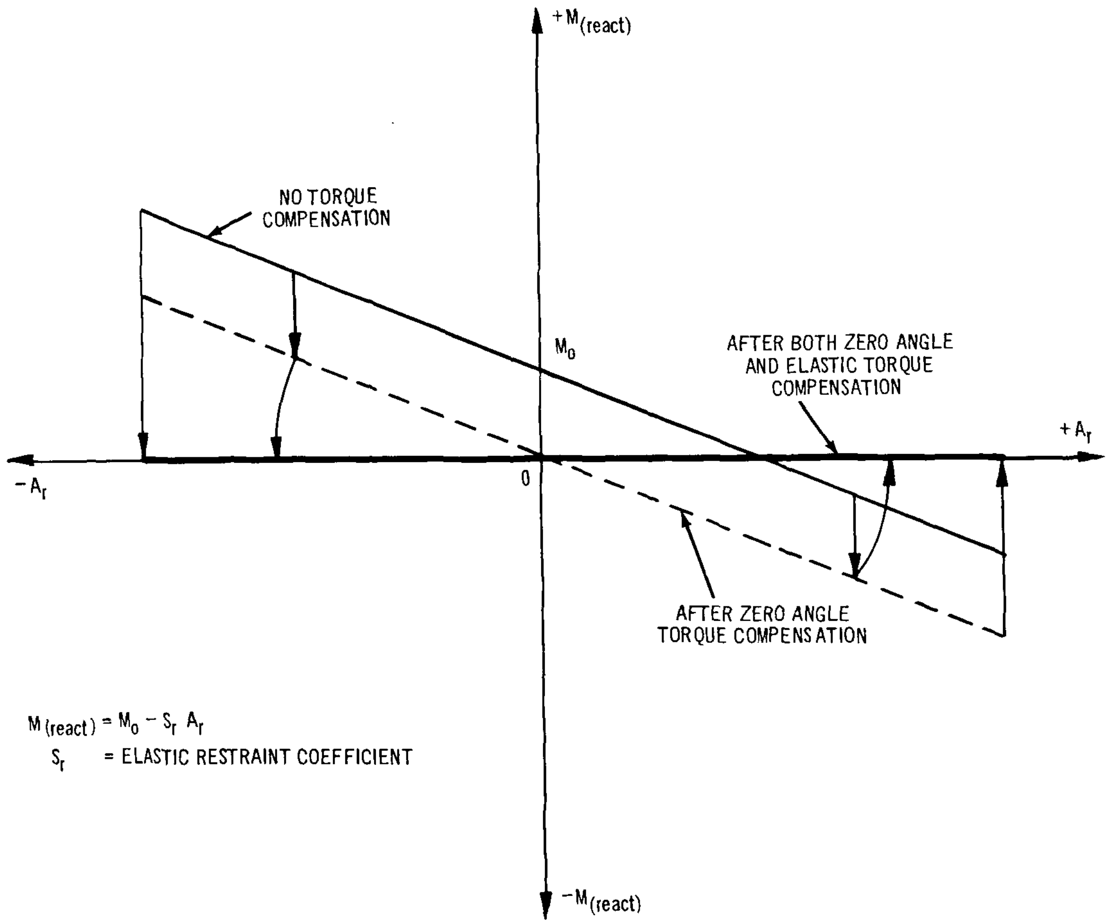


Fig. 6-2. Microsyn reaction torque and its compensation.

The M_o term is easily compensated by feeding a current into the tuned-secondary of the torque generator, this current coming from the input voltage, as shown in

Fig. 6-3. The elastic restraint torque is compensated for by feeding a current into the tuned-secondary of the torque generator from an amplifier whose input is the signal generator output voltage as also shown in Fig. 6-3. Note that both component compensators have a positive and negative range about a zero position. Since the reaction torque, $M_{(react)}$, is proportional to the square of the excitation current (and excitation voltage) it can be shown that both component torque compensations are excitation voltage and current insensitive. Therefore, once this torque is compensated for, it need not be considered again.

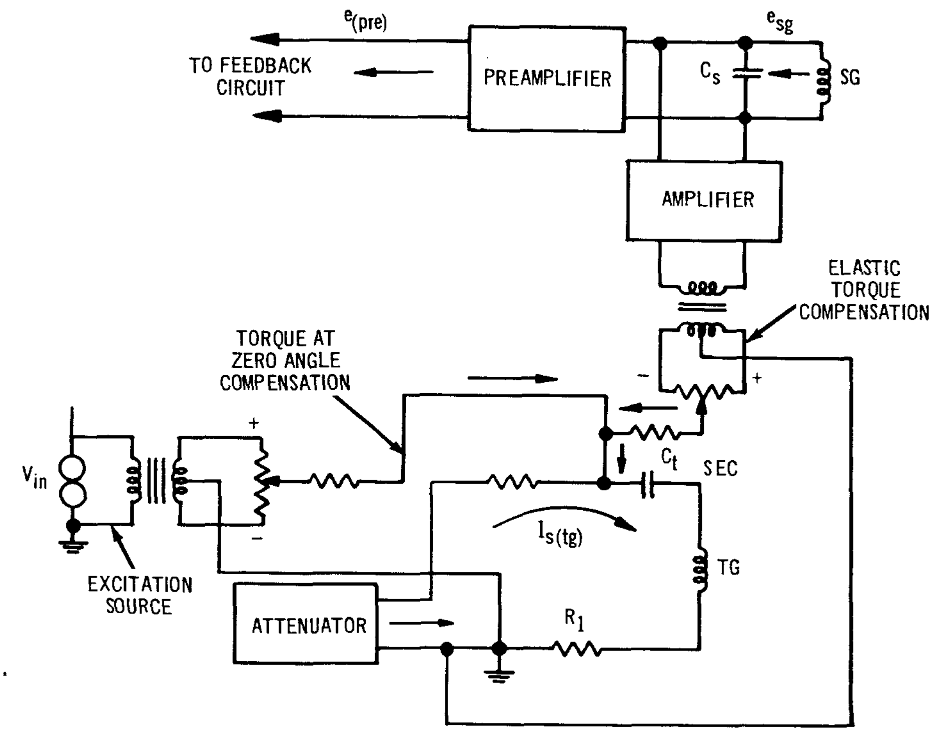


Fig. 6-3. Schematic diagram for the reactor torque compensation.

6.3 Signal Generator Quadrature and Harmonics

The main reason for minimizing the signal generator null-voltage quadrature and harmonic components is that they tend to saturate the later feedback amplifier stages as well as to overload the secondary of the current-product resolver with useless, heat-producing currents. Although the current-product resolver

will discriminate well against quadrature and harmonic currents; this discrimination is only as good as the primary current is free of quadrature and harmonic components. Therefore, a judicious designer minimizes both of these components. The quadrature voltage is easily compensated for by trimming the signal generator. primary circuit with a proper resistor, as shown in Fig. 6-4. The harmonics are minimized by using the proper microsyn air gap length and secondary turns with the excitation frequency. This, coupled with the signal generator secondary

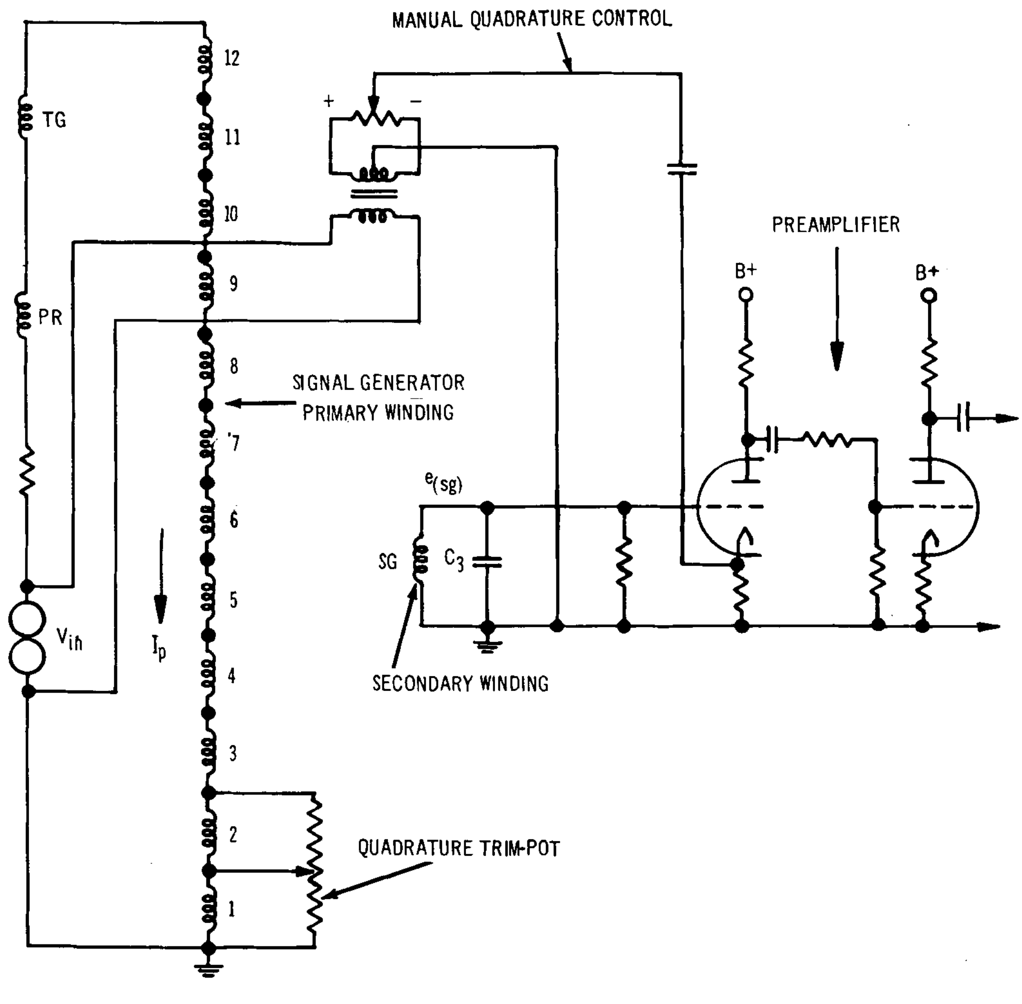


Fig. 6-4. Quadrature voltage compensation in a 12-pole microsyn.

condenser, keeps the harmonics within due bounds. In order to take care of any quadrature "pick-up" along the feedback amplifier circuit an accessory manual quadrature control is used that adds a quadrature compensation voltage to the bias resistor of the first stage of the feedback circuit preamplifier, as shown in Fig. 6-4. This circuit is helpful in setting the alignment of the phase of the over-all circuit. Also, it conveniently allows a given amount of quadrature voltage to be introduced in order to properly trim the feedback phase-adjustment. Note, by Fig. 6-1, that a quadrature voltage introduced after the signal generator circuit will not cause any signal generator secondary quadrature current, I_{qs}, to flow. It will, however, cause a torque-generator and current-product resolver secondary quadrature current to flow. If the feedback circuit phase is exactly correct, these respective quadrature currents will be in quadrature with the common primary excitation current and no torque on the torque generator or product resolver systems will result. Hence the feedback circuit is properly phase-aligned.

6.4 Torque Generator Quadrature and Harmonics at Null

Since the torque generator null voltage, which may consist of quadrature and harmonic voltages, represents a "back-emf" looking back at the attenuator, it results in an indicated torque undertainty in the readout system. For example, if the output of the attenuator is 10 millivolts, representing the voltage necessary to balance a low externally applied torque, and the torque generator null is 100 millivolts of quadrature and harmonics, the torque generator secondary current is more a function of its own null voltage than the proper feedback voltage. This results in a sluggish, variable type of torque reading which is typical of an uncertainty torque. The torque generator output voltage harmonic content is minimized by the proper design of winding, core, frequency, excitation and air-gap length. The quadrature voltage can be corrected in exactly the same manner as the correction in the signal generator. However a simpler scheme is suggested. A compensating quadrature voltage is fed from the input voltage, $V_{(in)}$, to a resistor, R_1, between the torque generator coil and the ground point, as shown in Fig. 6-5. The capacitor, C_q, shifts the phase of the compensating voltage ninety degrees in order to generate a quadrature voltage. The center-tapped transformer and potentiometer allow both plus and minus quadrature compensation.

6.5 Signal and Torque Generator Null Voltage Angular Misalignment

If the signal generator and the torque generator angular null voltage position do not coincide, even with careful assembly, another type of "back-emf", due to the torque generator, will appear. This is because in this "closed-loop" torque

system the signal generator is constrained to operate at its null voltage angular position with no torque applied. However, the torque generator secondary will be generating some output voltage if its rotor is misaligned with the signal generator rotor. Therefore, another fixed voltage signal is also added to the resistor, R_1, (in Fig. 6-5) coupled by a resistor, R_i. This adds a corrective "in-phase" signal to the torque generator secondary, which apparently "shifts the null position" to coincide with that of the signal generator.

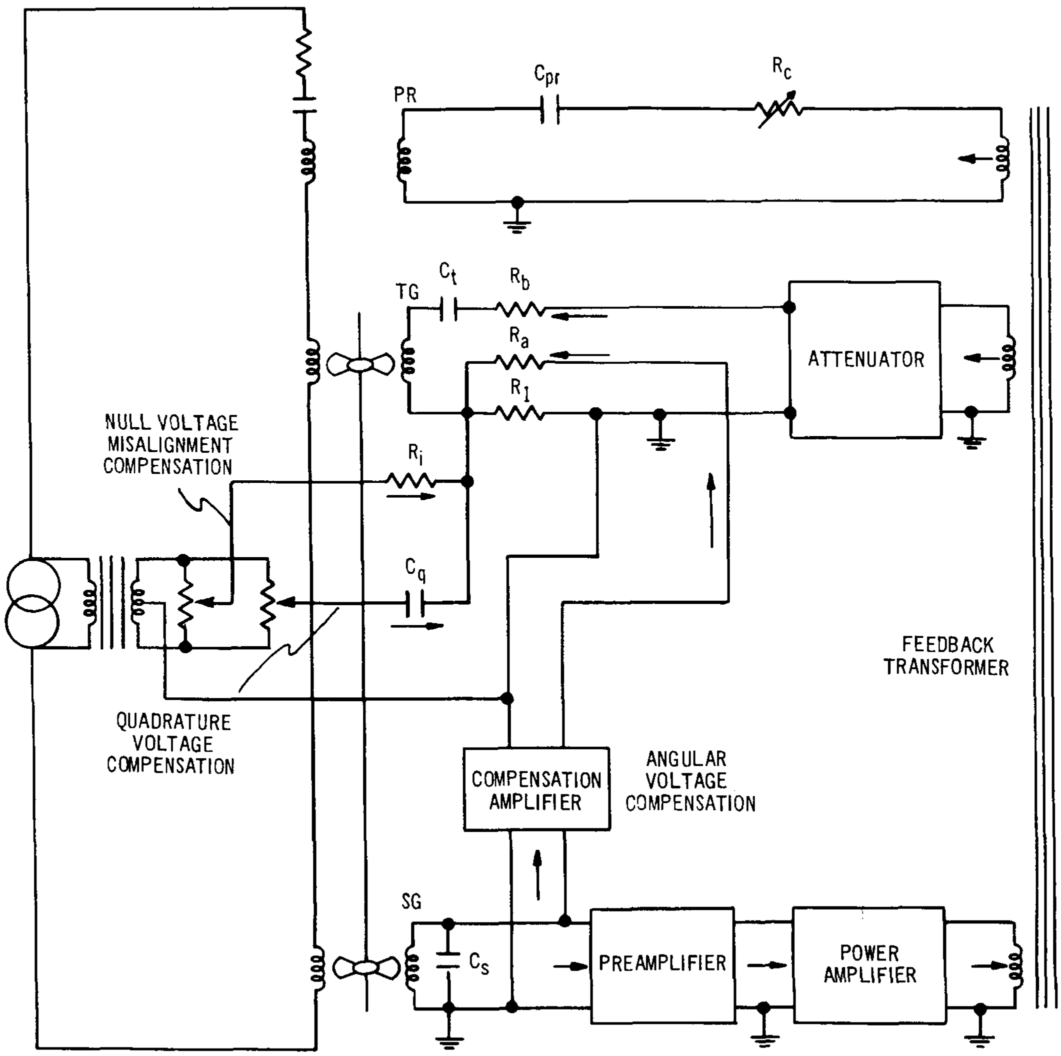


Fig. 6-5. Torque generator back-emf compensation.

6.6 Torque Generator Secondary Output Voltage with Rotor Angular Displacement

This is the output voltage with microsyn rotor rotation from its zero or null position and corresponds to the useful output signal from the signal generator, which detects the angular rotation of the torque-summing-member. However, in the case of the torque generator secondary output voltage, it represents an apparent torque generator secondary circuit impedance change, with shaft rotation, as seen by the attenuator. It is imperative in the proportional and adaptive elastance types of torque measuring systems that both the torque generator and current-product resolver secondary circuit impedances remain constant for precise results. It then becomes necessary to compensate for this angular voltage signal from the torque generator.

This is quite easily accomplished by connecting another compensating circuit to the resistor, R_1, (see Fig. 6-5) through the resistor R_a. This angular compensating voltage is derived from the signal generator angular voltage through a compensating amplifier whose gain is set to just compensate for the torque generator back voltage. The torque generator circuit attenuator now sees a small constant null voltage even over the largest angular range of the torque-to-balance loop.

6.7 Attenuator Leakage Impedance

This leakage impedance is an insidious one and is usually only apparent to those experienced with this type of leakage. Since the attenuator dictates the correct voltage on the output of the feedback transformer to feed the secondary circuit of the current-product resolver readout, any current that "sneaks by" the attenuator into the torque generator secondary results in a corresponding error in the torque readout.

Figure 6-6 will help make this condition clear. Assume a general leakage impedance around the attenuator of some arbitrary value of resistance, inductance and reactance. If it were possible to feed a negative compensating current equal and opposite to the positive leakage current into the series-resonant torque generator secondary, the net leakage current into the torque generator secondary winding would be zero. This negative current is obtained by feeding the negative side of the grounded center-tapped feedback transformer winding voltage through both a capacitor and a resistor circuit to the series-resonant torque generator secondary winding. The capacitor current, I_c, can compensate for both the leakage capacitance and inductance because this leakage is mainly capacitive. The resistor current, I_R, can compensate for the leakage resistance. The capacitor potentiometer, P_c, is adjusted until the torque indication reads zero, (with no externally applied

torque), when 50 milliamperes of quadrature current is made to flow into the product-resolver series-tuned secondary. This quadrature current comes from the quadrature voltage compensator in the feedback circuit as shown in Fig. 6-4. If there is leakage reactance, a secondary current, I_ℓ, will flow in the torque generator secondary with a component in phase with the common primary current. This will apply a torque to the torque-summing-member and the readout will indicate this torque. By adjusting the potentiometer, P_c, until this torque is zero, the leakage impedance is compensated.

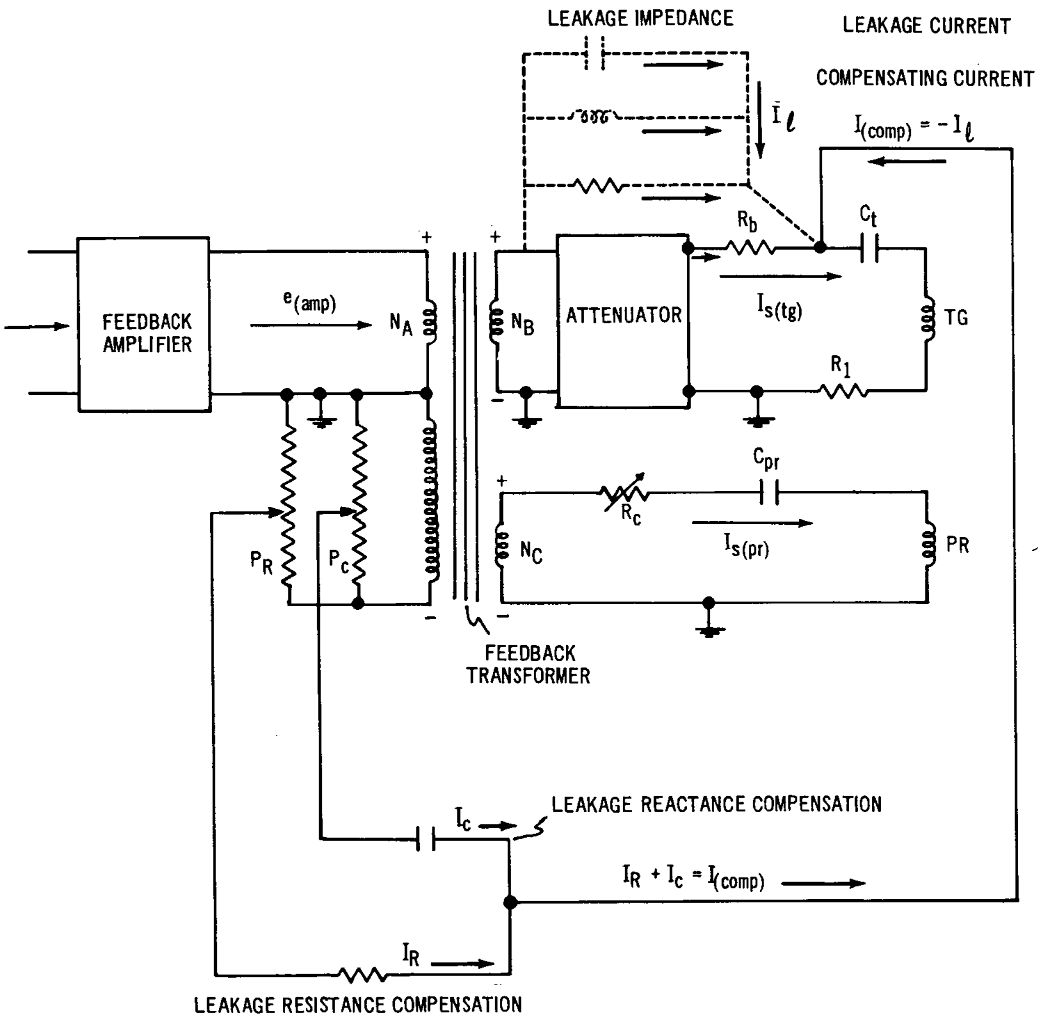


Fig. 6-6. Torque generator secondary leakage impedance compensator.

The leakage resistance effect is manifested by a torque generated, with angular displacement, which is indeed an elastic torque. It is very small and is only apparent at extremely low torque levels. By adjusting the potentiometer, P_R, such that no small elastic torque exists, the leakage resistance becomes compensated.

6.8 Core Hysteresis Effects

This strange effect, called "a-c hysteresis" by the authors, is strongly reminiscent of "viscous hysteresis" in dielectrics. In the differentially wound microsyns, a change in secondary winding a-c current with the primary excited, followed by a return to zero excitation, is often followed by some residual torques. A quadrature voltage also exists on the secondary terminals. It can be somewhat minimized by temporarily overexciting the respective signal and torque generator primaries with twice the normal current, thence to zero and back to normal.

6.9 Base Motion Effects

Base motion effects refer to those torques resulting from random motions of the torque-summing-member's support base. If the center of mass is not on the axis of rotation, horizontal accelerations (vibrations) of the base result in torque deviations. Concurrently, if the axis of rotation of the member is caused to deflect from the vertical because of some instability of the base, a gravity accelerational torque will result. Therefore, it is necessary to use a well-balanced rotating member together with a firm base support.

CHAPTER 7

MISCELLANEOUS ACCESSORY EQUIPMENT

7.1 Gas Bearing Supported Torque-Summing-Member

Throughout the discussion so far, only a "frictionless" supported torque-summing-member has been assumed. It must be pointed out, however, that both the torque-summing-member support and the associated circuitry previously described share equal roles of importance in the culmination of a precise torque measuring instrument. Therefore, a gas-bearing supported member must be considered.

The gas, or air-bearing device consists of a vertical rotatable torque-summing-member, supported in three dimensions by a pressurized bearing as shown in Fig. 7-1. Attached to the shaft are rotors of four devices; a microsyn signal generator, a microsyn torque generator, a viscous damper, and the air-bearing. The functions of the two microsyns have been previously described. The viscous damper may be a "paddle-wheel" type with a viscous oil, or an electromagnetic type. The latter is preferred because of its inherent neatness as compared to a fluid type.

The air is brought in from a 20-60 psi regulated supply through a millipore filter. An air drier is employed in order to eliminate water condensate on the bearing surfaces. With proper machining and assembly the frictional torque is less than 0.0001 dyne-centimeters. Even with careful machining a small auto-rotational torque, which is some function of the air pressure, does exist. Hence, some form of "air-torque" compensation is recommended. This can be accomplished by "bleeding-off" a small amount of air through a rotatable nozzle piece, which can be rotated until the air-torque is essentially zero.

The radial and vertical compliance or stiffness of the supported member depends on the air pressure, and a minimum allowable pressure is usually recommended. If the air pressure is too high, turbulence sets in at the bearing surfaces and a "roughness torque" results. Therefore, a maximum allowable pressure is also recommended.

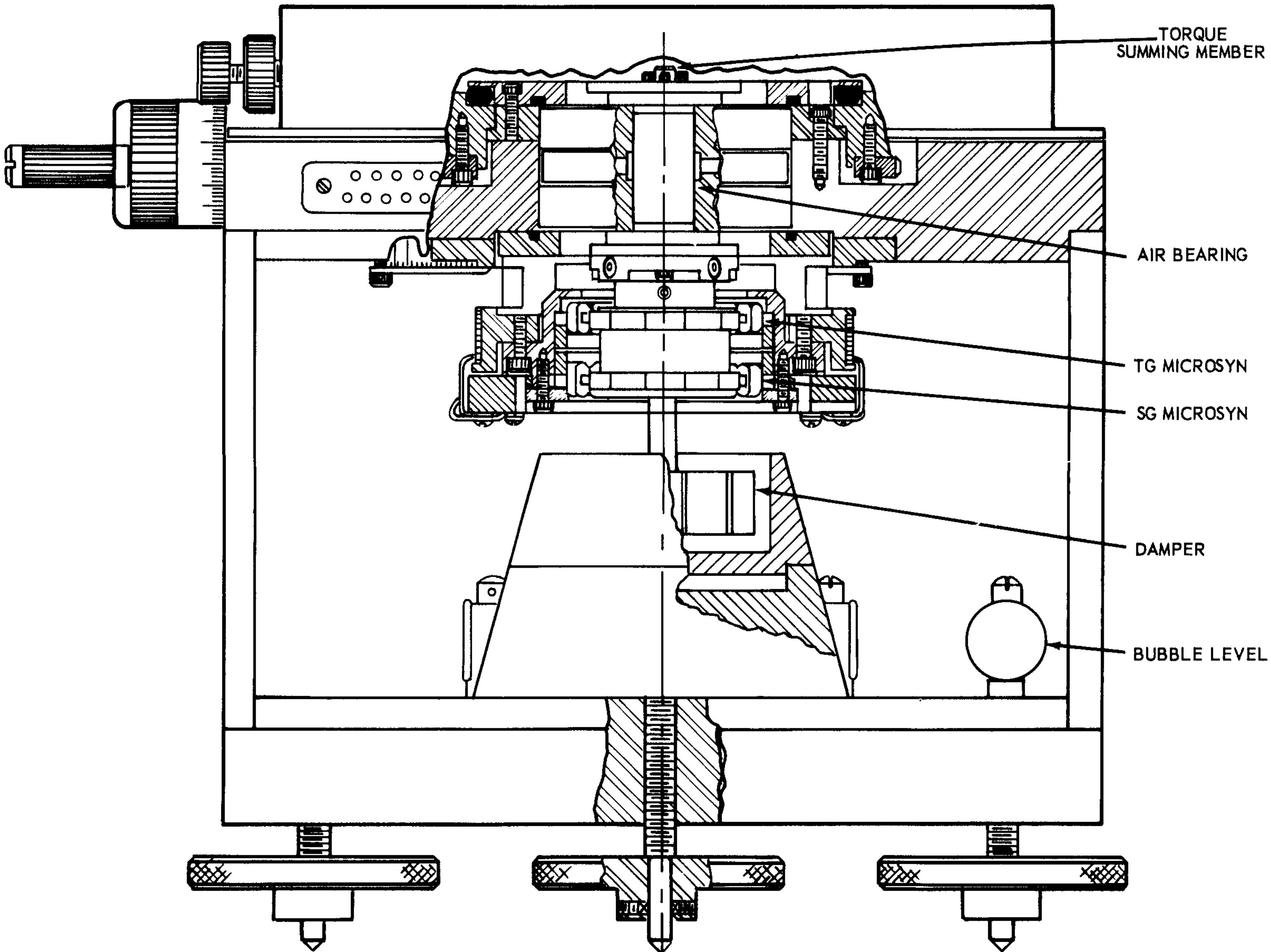


Fig. 7-1. Air bearing torque-summing-member.

7.2 The Signal or "Dummy Director"

It is frequently useful to examine the externally applied torque over some angular range about the torque-measuring-system zero angular position. An example of this might be to measure the so-called "elastic restraint" of the device whose torque is being tested. This could be accomplished by rotating this device with respect to the air-bearing case. However, this is difficult to do without accidentally introducing small radial displacements of the test device with respect to the torque-summing-member. Therefore, a method has been devised where various values of voltages can be summed, together with the signal generator signal voltage, into the preamplifier. See Figs. 7-2 and 7-3. If a voltage that is in phase with the signal generator output signal, is fed into the cathode bias resistor of the first stage of the preamplifier, the signal generator output signal will "back up" until the original voltage value is reached at the output of the first stage of the preamplifier. This is inherent in any "closed-loop" system wherein the net signal input to the feedback circuit is maintained at its original value, if the external torque applied remains constant. Hence, the torque-summing-member will rotate in a reverse direction and by an amount equal to the angle needed for the signal generator to develop an equal voltage. This "dummy director" is also used to measure the elastic restraint component of the sum of the signal and torque generator reaction torques. The elastic torque is then minimized over the useful angular range of the instrument, as previously described.

7.3 Zero Angular Deflection Mode

The dummy director has a far greater function in that it can be used to zero the angular deflection of the torque-summing-member shaft. This is done repeatedly in order to reduce error torques due to changes in the angular position of the shaft. The dummy director voltage can be adjusted manually until the signal generator output signal voltage reads a null value, which is a case of integration with the operator as part of the feedback system. The integration can be performed automatically by servo driving the dummy director potentiometer, through the proper gear reduction, from the signal generator output signal. This automatic integration, which keeps the steady-state angular deflection of the torque-summing-member zero, increases the response time. However, in many cases of low torque level measurements, the increase in characteristic time is well justified.

This zero angular deflection mode may be used with either of the three types of elastance discussed. In the adaptive elastance system it facilitates the measurement of torque to a high degree of resolution, which is accomplished by what is known as the potentiometric measurement of torque.

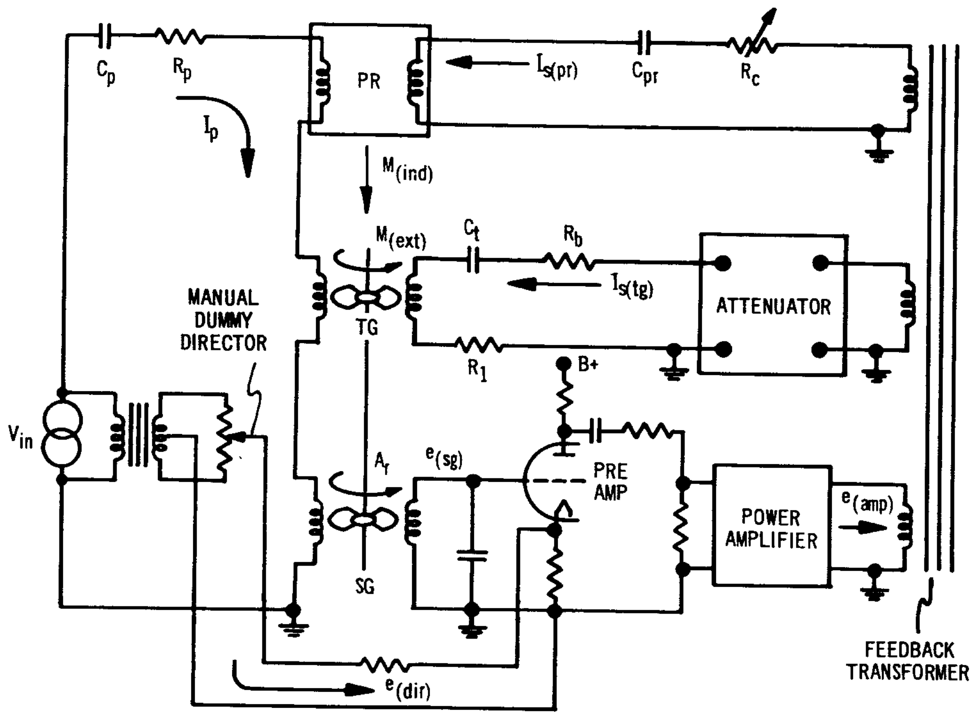


Fig. 7-2. Schematic diagram of torque measuring system showing signal or dummy director.

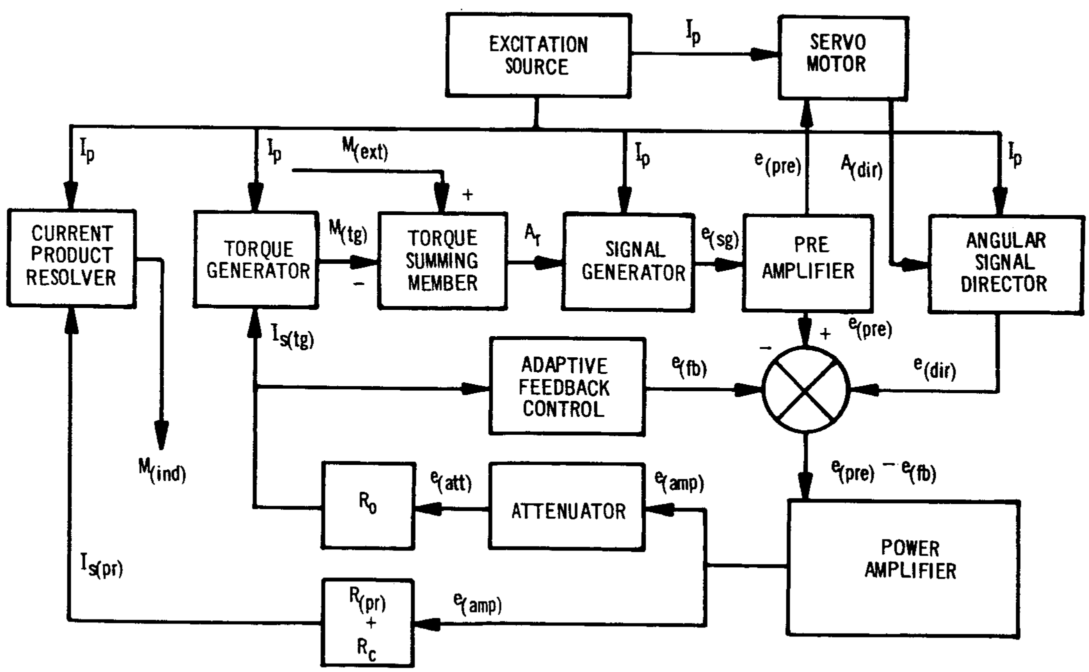


Fig. 7-3. Block diagram of torque measuring system showing signal or dummy director.

7.4 The Potentiometric Measurement of Torque

It was pointed out in Chapter 4 that the attenuator decade-setting GD, or "attenuation" is equal to the full-scale output of the product-resolver direct-current amplifier, as long as the device is properly calibrated. In other words, when the direct current output meter reads 1.00, full scale, the attenuator setting gives the value of the external torque. Then, if it were possible to accurately read this full-scale position, the attenuator setting, which is now the external torque, could be read to as many significant figures as the attenuator has decades. A scheme for expanding the full-scale direct current output, 1.000 milliamperes, was devised by using a sensitive galvanometer whose center-reading zero coincided with the full-scale direct-current output. This is shown in Fig. 7-4. The reversing switch will balance either the positive or the negative output of the product-resolver. If the dropping resistor, R, is equal in ohms to 1000 times the rated constant voltage of the reference solid-state d. c. voltage-source, the galvanometer, G_a, will read zero when the product-resolver output is at its full-scale output of 1.000 milliamperes. If the galvanometer is sensitive enough it can detect changes of one part in one thousand of 1.000 milliamperes. This corresponds to a change of one part in one thousand units of the full scale torque setting on the attenuator. For example, if the attenuator setting, GD, reads 0.8432 dyne-centimeters of torque, a change of the fourth decimal place could be detected. Hence the attenuator can be used as a potentiometer in measuring the value of the applied torque to four significant figures. However, this presumes that the overall torque uncertainty is better than ± 0.0001 dyne-centimeters. This low uncertainty is quite difficult to obtain and requires excellent air and magnetic torque compensation as well as a stable air-bearing support base.

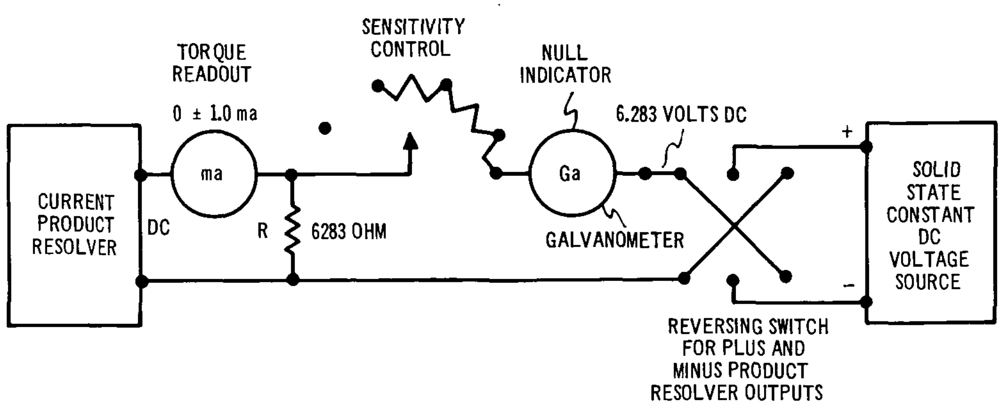


Fig. 7-4. Schematic showing method of expanding the full-scale direct current output of the current-product resolver.

CHAPTER 8

TORQUE MEASURING APPLICATIONS

8.1 Measurement of Single-Degree-of-Freedom Gyro Performance

In 1958, Gilinson, Lattanzi* and Scoppettuolo successfully used a multirange a-c torque system of the proportional elastance type, see Fig. 8-1. It was used to measure the performance of certain Draper** floated gyros.[7] Its mode of operation

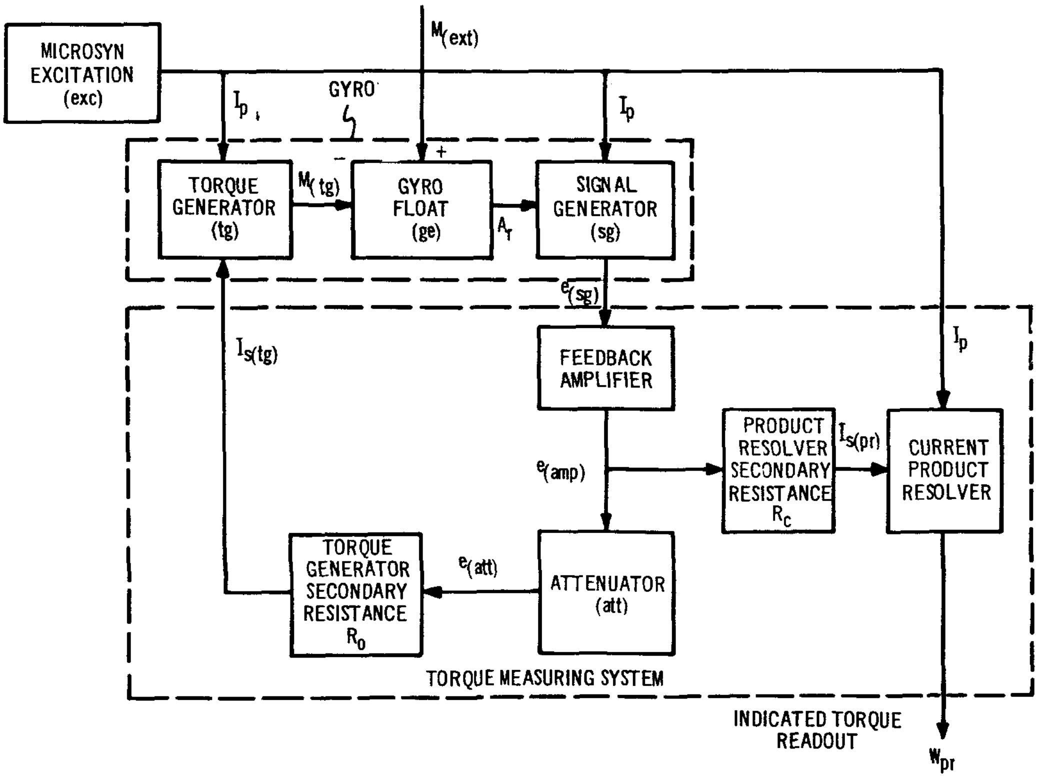


Fig. 8-1. The ac torque measuring system applied to gyro performance.

*Andrew C. Lattanzi, Chief Test Engineer, Minicom Group, Instrumentation Laboratory, M. I. T.

**C. S. Draper, Professor and Head of the Department of Aeronautics and Astronautics, and Director of the Instrumentation Laboratory, M. I. T.

is similar to the air-bearing supported torque-summing-member, except the floated gimbal is now the torque-summing-member. Each gyro contains a microsyn signal generator and a microsyn torque generator with which the torque measuring system can be coupled. Many performance characteristics can be studied by means of this system such as compliance, drift rates, torque deviations, gas bubbles in the flotation fluid etc.

This system is an excellent means for obtaining proper gimbal balance. A great deal can be learned if the general torque deviations in a single-degree-of-freedom gyro are expressed as a series function of the gravity term.

$$(D)\,M = A_o\, g^0 + A_1\, g^1 + A_2\, g^2 + A_3\, g^3 + \cdots$$

$$= \sum_{n=0}^{\infty} A_n\, g^n \tag{8-1}$$

where

$(D)M$ = torque deviation from its ideal or specified performance value

$A_0 g^0$ = gravity insensitive torque

$A_1 g^1$ = mass unbalance torque

$A_2 g^2$ = gimbal compliance torque

$A_3 g^3$ = "g-cubed" torque

It now becomes possible to evaluate these terms by means of a Fourier analysis of the torque deviation, as traced on a recorder. This is usually done by mounting the gyro on a turn-table whose axis of rotation is parallel to the earth's axis. The input axis of the gyro is set perpendicular to the earth's axis to null the earth-rate torque. The table is then caused to rotate at various constant angular velocities, particularly earth's rate, with an a-c multirange torque measuring system connected to it. As the orientation of the local gravity vector sweeps through a conical locus whose vertical angle is twice the complement of the latitude angle, the effect of the so-called "g" terms becomes effective. The direct current torque-recorder thus shows a periodic trace as the turn-table rotates through 360 degrees.

Since different integrating gyros usually have different microsyns, it is not always practical to connect the two microsyn primaries in series with each other, together with the current product resolver primary. Also the signal and torque generator secondary impedances may be quite different. Therefore, a means of flexible impedance matching is used in order to couple this measuring system with

gyros of various microsyn impedances. This is shown in Fig. 8-2. Note the impedance matching transformer in the torque generator secondary circuit. The three 10-ohm resistors in the primary circuits are for current magnitude and phase monitoring. The torque generator secondary circuit resistors, R_1 and R_2, are also for magnitude and phase monitoring. The preamplifier usually takes care of most signal generator secondary impedances met in practice.

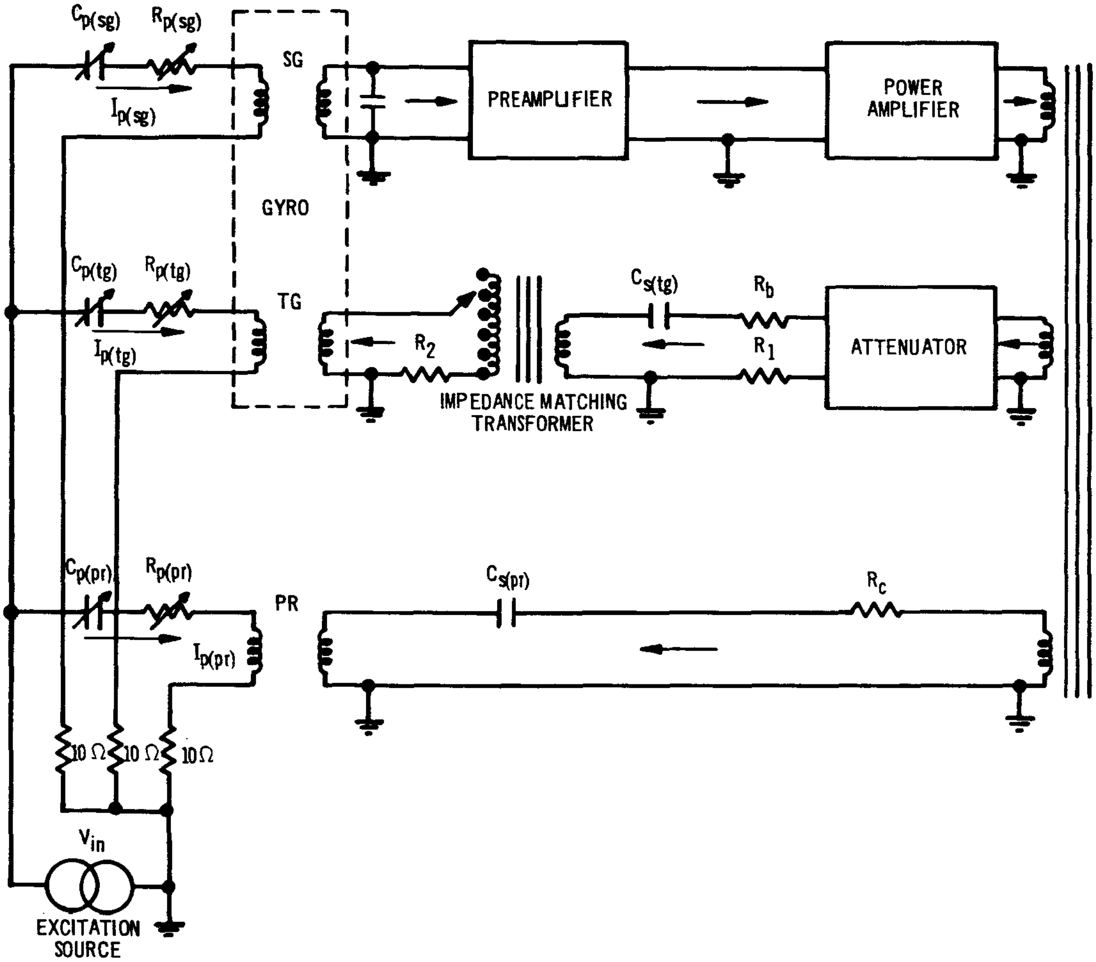


Fig. 8-2. Parallel excitation of gyro microsyns and current product resolver.

8.2 Gyrocompass Application

A good application of this type of torque-to-balance loop is in the gyrocompass field. If a single-degree-of-freedom integrating gyro is mounted with its output axis perpendicular to a "local vertical" platform, the input axis receives the horizontal component of the earth's angular velocity. The direct current output

from the product-resolver will indicate the particular horizontal component of the earth's angular velocity. Remember that with a particular gyro, the system can be calibrated to indicate earth's rate instead of torque. The horizontal component of earth's rate in terms of the azimuth angle, measured from the east-west meridian is

$$W_{IEh} = W_{IE} \cos L \sin A_z \tag{8-2}$$

where

W_{IE} = earth's angular velocity about its own axis

A_z = azimuth angle in radians, measured from the east-west meridan

L = latitude angle

Note that with the input-axis pointing either east or west the azimuth angle, A_z, is zero and no output from the product resolver will result. Hence, there are two solutions 180 degrees apart. If a second floated integrating gyro is similarly mounted to the "local-vertical" platform, except that its horizontal input axis is 90 degrees from that of the first gyro, a unique solution exists. Its equation with respect to the azimuth angle is, referring it to the input axis of the first gyro

$$W_{IEh} = W_{IE} \cos L \cos A_z \tag{8-3}$$

When the input axis of the first gyro points east and the input axis of the second gyro points north, the output of the first gyro is zero while the output of the second gyro is a positive maximum. Conversely, when the input axis of the first gyro points west and the input axis of the second gyro points south, the output of the first gyro is again zero, but the output of the second gyro is a negative maximum. This information can now be controlled into a closed-loop system, such that if the "local-vertical" platform is free to rotate in azimuth, true north can be indicated.

8.3 Measurement of Single-Degree-of-Freedom Pendulous Accelerometer Performance

Wrigley* has suggested the use of this torque measuring system for either measuring the performance of pendulous accelerometers or using it in actual guidance control systems, particularly one which would track the so-called

*Walter Wrigley, Professor of Aeronautics and Astronautics, and Educational Director of the Instrumentation Laboratory, M. I. T.

"local-vertical" over the face of the earth. It is felt that the multirange feature of this torque measuring system would make the device an invaluable tool in the evaluation of pendulous accelerometer performance over the range of inputs from 0 to ± nG's up to the maximum torque capabilities of the instrument.

8.4 Measurement of Viscosity

In the measurement of viscosity,(5) this instrument holds a position of pre-eminence over other types of viscometers. It is particularly unique in the measurement of low viscosity-low shear rate characteristics of non-Newtonian fluids, such as protein solutions, DNA, etc. E. W. Merrill* has collaborated with the authors in the design of a sophisticated instrument known as the GDM viscometer.

Most viscometers in use today require a tremendous amount of time (hours) to make a run, or test one solution. This is particularly true with low viscosity, non-Newtonian fluids. These viscometers also require large geometric dimensions to obtain measurable torques with low viscosity liquids. This can be too expensive with some fluids, namely, fresh blood. The adaptive elastance loop can reduce not only the quantity of liquid required but also cut the test time down to seconds instead of hours. Figure 8-3 shows a schematic of the Couette cup and bob used with the GDM viscometer. The cup is attached to the air-bearing torque-summing-member. The cylindrical bob is driven by a multirange constant speed motor drive. By various motor drive speeds, the viscous shear torques at various viscous shear rates may be measured. It is quite necessary that the instantaneous rotational speeds of the bob be constant, otherwise any angular velocity modulations on the average angular velocity are reflected as torque modulations on the measured output average torque.

Its primary use in DNA (Deoxyribonucleic acid) viscosity measurements is in the determination of its molecular weight. This is accomplished by measuring what is called "intrinsic viscosity". Intrinsic viscosity is defined as

$$\eta_{(int)} = \lim_{c \to 0} \frac{\eta_{(solution)} - \eta_{(solvent)}}{\eta_{(solvent)}\, C} \qquad (8\text{-}4)$$

where

$\eta_{(int)}$ = intrinsic viscosity

$\eta_{(solution)}$ = viscosity of the DNA solution

*Edward W. Merrill, Associate Professor of Chemical Engineering, M. I. T.

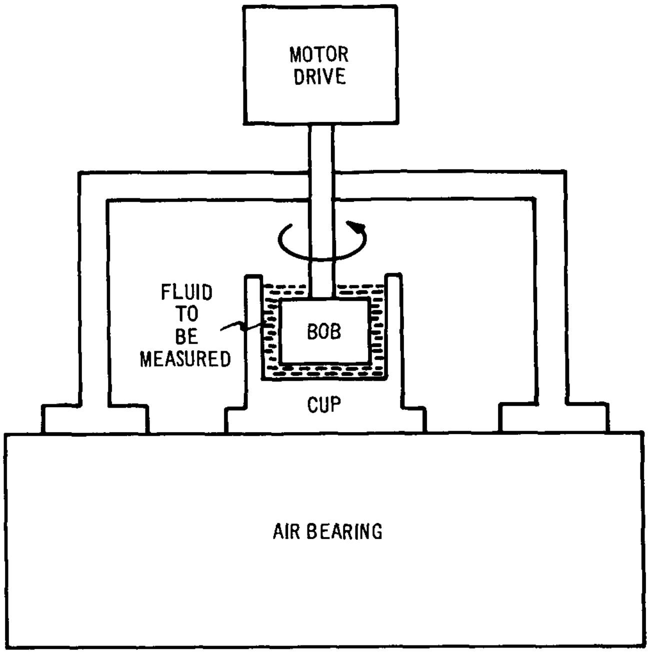


Fig. 8-3. GDM viscometer Couette cup and bob with motor drive.

η(solvent) = viscosity of the solvent

C = concentration of solution

In this determination, as the concentration approaches zero, the viscosity and resultant torque of the solution approaches the viscosity and resultant torque of the solvent, which is quite small. However, since large quantities of the DNA become prohibitively expensive to prepare, this viscometer was designed to hold 3-5cc in its Couette type viscometer head. This results in a very low shear stress, or torque, corresponding to the viscosity of a small amount of the liquid. Furthermore, by Eq. (8-4) it is necessary to obtain the difference between two small numbers whose magnitudes are almost equal. For example, the respective torques corresponding to the viscosities in the intrinsic viscosity determination at 0.2 rpm are:

$$\left.\begin{array}{l}\eta(\text{solution}) \sim 0.7534 \text{ dyne-cm} \\ \eta(\text{solvent}) \sim 0.7365 \text{ dyne-cm}\end{array}\right\} \text{ at a shear rate of } 0.2 \text{ rpm}$$

$$0.7543 - 0.7365 = 0.0169 \text{ dyne-cm}$$

Thus it becomes necessary to use the potentiometric method of measuring torque as described in Section 7.4.

Since the viscosity of most fluids is a function of its temperature, some means of temperature control or indication of the fluid must be provided. This is accomplished by causing a flow of water, whose temperature is accurately controlled, into the hollow rotatable cylindrical bob and out again.

8.5 Slow Speed Tachometer

As a direct postulate of the instrument's use as a viscometer, the measurement of slow instantaneous angular velocities may be realized. The range of angular velocities include from 0.001 rpm to 10 rpm. This is accomplished by the use of the same type of Couette viscometer cup and bob with a Bureau of Standards type of oil, with an accurately known Newtonian viscosity, as a function of temperature. Not only can the average rotational speed of a device be measured, but also its instantaneous rotor speed with time. This is done by means of a strip-chart recorder which traces the speed modulations, if any, as a function of time as indicated by the linear speed of the chart paper. By suppressing the torque resulting from the devices average rotational speed, its rotational speed deviations or modulations from its average speed may be measured on an expanded scale strip chart.

8.6 Seismograph for Horizontal Accelerations

Mr. Ken Tsutsumi of the Jackson & Moreland, Inc., Machine Design Group at M.I.T. has suggested the use of this instrument as a seismograph for the measurement of low frequency accelerations in the horizontal plane. This is accomplished by mounting a device on top of the air-bearing rotating member with its center of mass a known horizontal radial distance from the vertical axis of rotation. The torque feedback system dynamics are adjusted, by reducing the loop gain, to increase the frequency response at low input frequencies. A strip-chart recorder is used to record the direct current output of the current product resolver. This is a torque which is a measure of the torque developed on the seismic element by horizontal accelerations on the reference frame of the air-bearing support.

8.7 Miscellaneous Torque Measurements

There are many other types of torque measurements which this multirange device will handle. A few of these are:

1. Microsyn torques
2. Torsion wire characteristics
3. Flex-lead torques

4. Hair-spring torques

5. Magnetometer and electrometer torques

Charles Perez* of the M. I. T. Instrumentation Laboratory has suggested the use of this instrument for the measurement of the power output of a LASER. This involves the measurement of torque produced by photon impulse forces acting on a light reflective surface. This surface is placed at a known radius from the axis of rotation of the air bearing torque-summing-member. Either pulsed or continuous wave (CW) LASERS may be measured. Some difficulty does arise, however, in the measurement of these special torques, if the new dynamic constants introduced are large compared to those of the main measurement system. This is particularly true when a device to be measured introduces both inertia and elastance to the torque-summing-member. An electro-magnetic type of variable damper has been introduced to take care of this situation. This is manually controlled at the discretion of the operator.

*Charles Perez in a private communication to C. R. Dauwalter, July 23, 1962.

CHAPTER 9

TEST RESULTS AND CONCLUSIONS

9.1 Sample Feedback Loop Parameters

The following list contains some of the more important parameters used in the three types of elastance loops discussed in this report. Most of these are the same for the three types, with the exception of the attenuation factor, DR_t, in the proportional and adaptive elastance case; and the adaptive feedback sensitivity, $S_{(ad)}$, and power amplifier gain, $S_{(amp)}$, in the adaptive case.

$S_{(tg)}$	-- 1.5 dyne-cm/ma^2
I_p	-- 50 milliamperes
$Q_{s(sg)}S_{(sg)}$	-- 71 millivolts/milliradian
$S_{(amp)(pre)}$	-- 1000
$S_{(amp)}$	-- 15 (except in adaptive case)
$S_{(amp)fb}$	-- 15000 ($S_{amp} \times S_{(amp)(pre)}$)
R_o	-- 20 K ohms
N_B/N_A	-- 1.0

This results in an overall loop elastance, $S_{(fb)c}$, in the constant elastance case of about 4000 dyne-centimeters per milliradian.

In the adaptive elastance case the negative adaptive feedback term, $\left(\frac{R_1}{R_o}\right) S_{(ad)}$, is adjusted to a value of 0.06, (See Eq. (5-3a)) and the power amplifier gain is set at 150. Since the attenuation term, DR_t, is proportional to the torque level it follows that the loop elastance for both the proportional and the adaptive elastance case will vary, as shown in Table 9-1.

Table 9-1. Loop elastance in dyne-cm/milliradian.

TORQUE LEVEL (dyne-cm)	CONSTANT ELASTANCE	PROPORTIONAL ELASTANCE	ADAPTIVE ELASTANCE
1000	4000	4000	4000
100	4000	400	2100
10	4000	40	370
1	4000	4	40
0.1	4000	0.4	4
0.01	4000	0.04	0.4

The angular deflections corresponding to these torque levels for the three cases are as shown in Table 9-2.

Table 9-2. Angular deflection in milliradians.

TORQUE LEVEL (dyne-cm)	CONSTANT ELASTANCE	PROPORTIONAL ELASTANCE	ADAPTIVE ELASTANCE
1000	0.250	0.2500	0.2500
100	0.0250	0.2500	0.0475
10	0.0025	0.2500	0.0270
1	0.00025	0.2500	0.0250
0.1	0.000025	0.2500	0.0250
0.01	0.0000025	0.2500	0.0250

It now becomes evident that a constant elastance type torque instrument cannot measure low percentage values of its full scale rating because the angular deflection is so small. This keeps the signal generator output well within its noise level and no angular displacement intelligence can be perceived by the feedback loop. Notice how neatly the adaptive elastance method adjusts its angular displacement to fit the torque level. It becomes a constant deflection type of instrument at the low end of the torque scale, and never dips below some prescribed minimum allowable value.

9.2 Sample Test Results

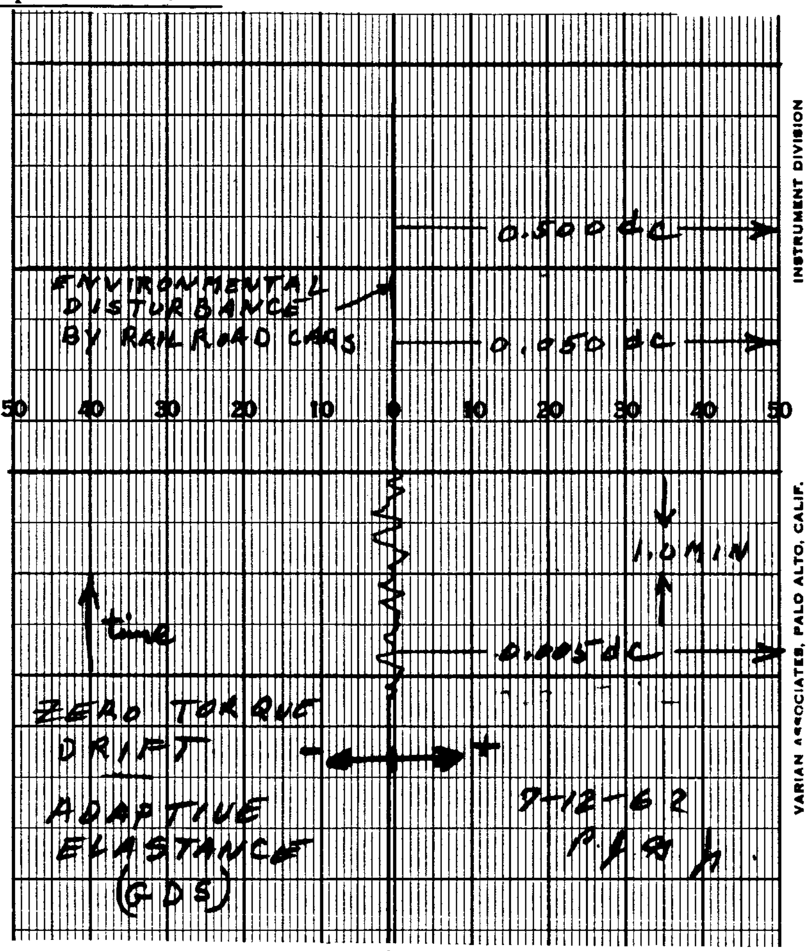


Fig. 9-1. Zero drift of the adaptive elastance (GDS) torque measuring system.

Figure 9-1 shows the zero torque drift with time on a full scale torque of 0.0050 dyne-centimeters, followed by full-scale settings of 0.05 and 0.5 dyne-centimeters. This is done with the adaptive elastance type of loop. Note the absence of noise on the trace. The apparent wandering of the trace on the 0.005 dyne-cm scale is due to motion of the air-bearing base support. Experience has shown that this is the principle source of torque deviations in the adaptive elastance (GDS) system.

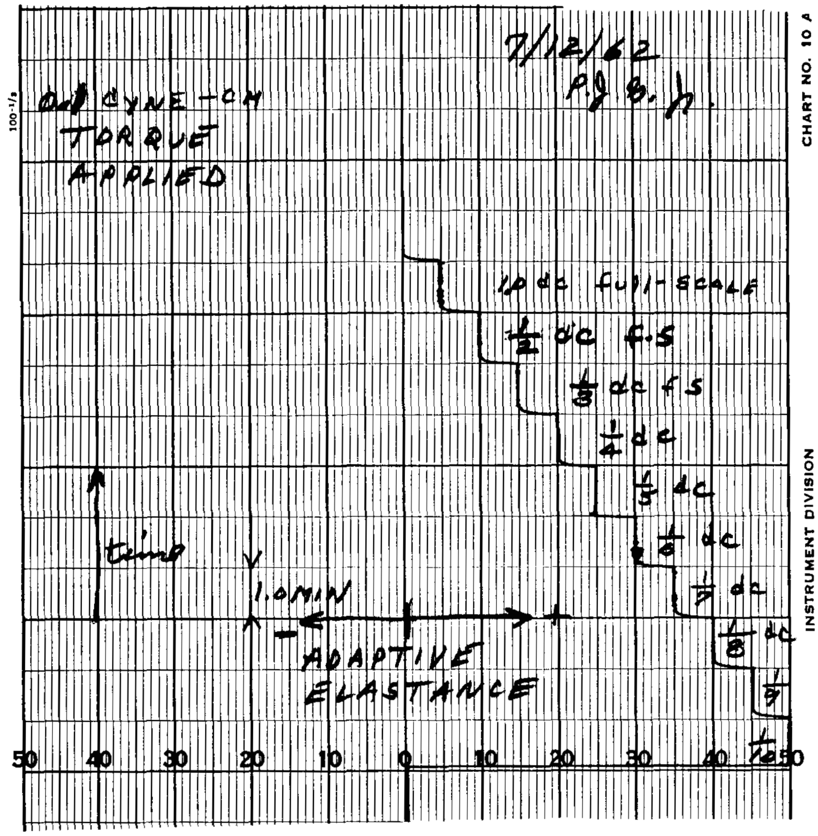


Fig. 9-2. Torque of 0.10 dyne-cm for 10 full scale settings of 1.0, 1/2, 1/3, . . . 1/9 and 1/10 dyne-cm.

Figure 9-2 shows an applied torque of 0.1000 dyne-centimeters on successive full-scale settings of 1/10, 1/9, 1/8, ...and 1 dyne-centimeters on the adaptive elastance (GDS) torque system.

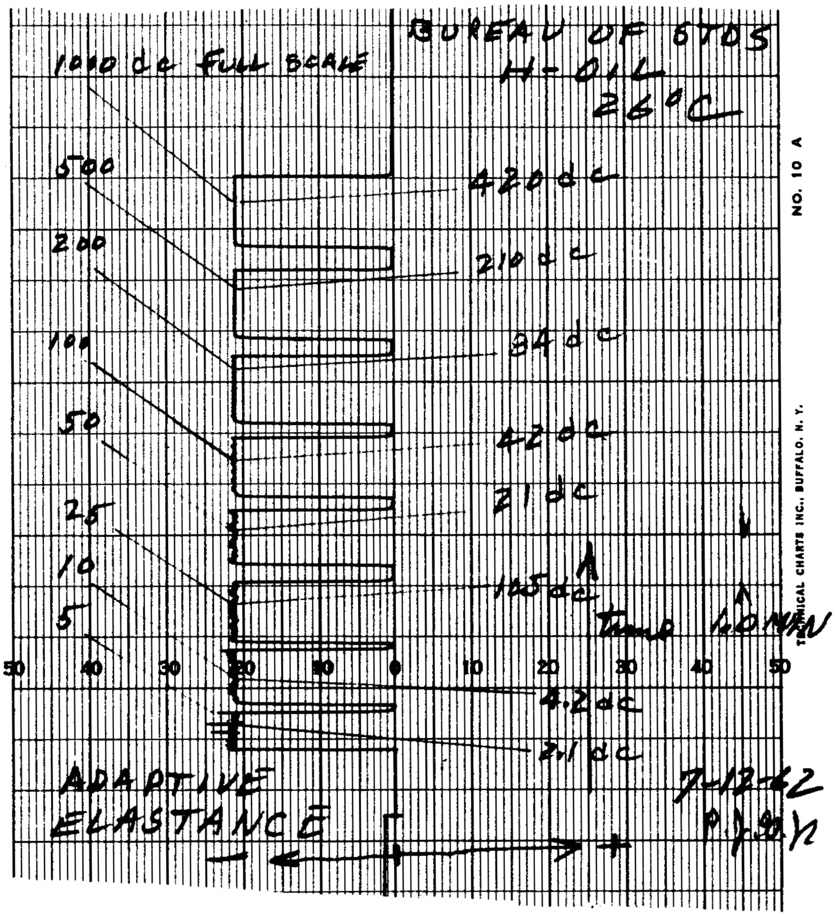


Fig. 9-3. Torque system used as rotational viscometer on Newtonian oil at successive speeds of 0.3, 0.6, 1.5, 3.0, 6.0, 12, 30, and 60 rpm.

Figure 9-3 shows torque ranging over many orders of magnitude with corresponding order of magnitude full-scale torque settings. Note that the trace settles out to a continuous straight line after the transient effects die out. These torques were applied by a Couette type of viscometer head rotating over a wide range of constant speeds.

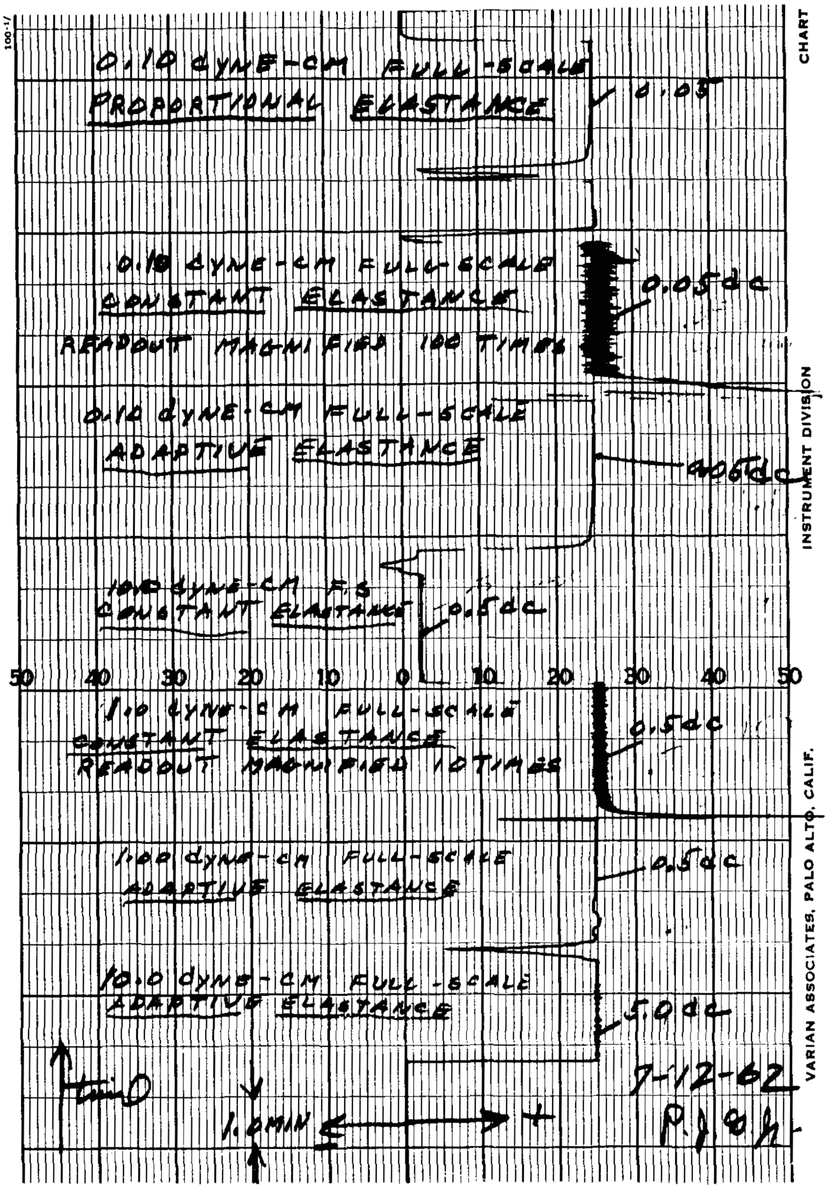


Fig. 9-4. Adaptive and constant elastance measurements of 0.05, 0.5 and 5.0 dyne-cm

Figure 9-4 shows torques of 0.05, 0.5, and 5.0 dyne-centimeters on the torque system using the constant, proportional and adaptive elastance methods. Note that the response times for the three levels of torque are equal in the constant elastance case. Note how long the response time is for the proportional elastance case at 0.05 dyne-cm. The noise level at 0.05 dyne-cm observed in the constant elastance test is reduced in the proportional and adaptive elastance cases.

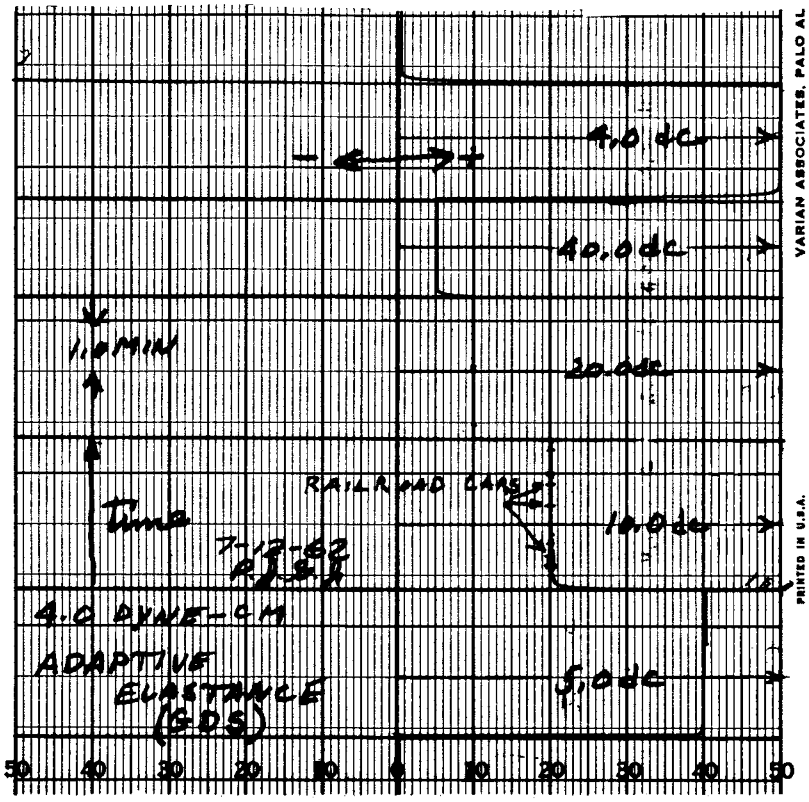


Fig. 9-5. A torque of 4.0 dyne-centimeters on five different torque scales.

Figure 9-5 shows a torque of four dyne-centimeters on five different full scale settings of the adaptive elastance (GDS) system.

In summary the advantages of each of the three types are as follows:

1. Constant Elastance - Relative low cost and simplicity. Constant characteristic time.
2. Proportional Elastance - The multirange feature and the automatic filtering of disturbing torques at the low end of the torque range.
3. Adaptive Elastance - The increased multirange feature and the reduction of the characteristic time at the low end of the torque range.

Thus, it is necessary that the user of such a device choose the type that more nearly suits his particular applications.

9.3 Conclusion

In this torque system, with the air-bearing vertically supported torque-summing-member, the stability of the base mounting is of prime importance. The largest source of torque drift or uncertainty is the slow undulating motion of the base support. In other words, the torque-summing-member does not remain exactly vertical. One method used to minimize these torque drifts is to balance the torque-summing-member, in two planes, while its axis of rotation is in the horizontal plane. This, together with a stable base mounting, reduces the torque uncertainties to near 10^{-4} dyne-centimeters. Figure 9-6 shows a block diagram of the multirange adaptive elastance (GDS) type of torque measuring instrument without any of the compensating networks except the rate-stabilizing lead-network.

It is recommended that any future development along the line of the a.c. multirange torque system include the following studies:

1. Lower torque-summing-member moment of inertia
2. Better base-motion stabilization of the torque-summing-member
3. Optimum size of electromagnetic components (microsyns) for torque measuring capacity
4. Constant current excitation with little or no transient effects
5. Constant gas pressure when gas pressurized bearing is used
6. Constant temperature environment.

If the instrument torque member has a low moment of inertia, the system dynamics are vastly improved, both from disturbing torques on the shaft and from disturbing inputs to the outer case.

Since most of the disturbing inputs come from the base motion it is quite appropriate to devote a lot of effort in accomplishing base stabilization.

If the electromagnetic devices are too small or overexcited, then the core nonlinear effects come into play and affect the reaction torque compensation. Some of the disturbing inputs come from transient variations in the excitation voltage and current. Stability of the excitation source is therefore quite useful. Similarly, if there are large perturbations in the gas pressure that is feeding the air-bearing, torque uncertainties result. Therefore, a smooth air supply is recommended. It has been noticed that the device is somewhat temperature sensitive, particularly noticeable at the low torque levels. Therefore, a constant environmental temperature is recommended.

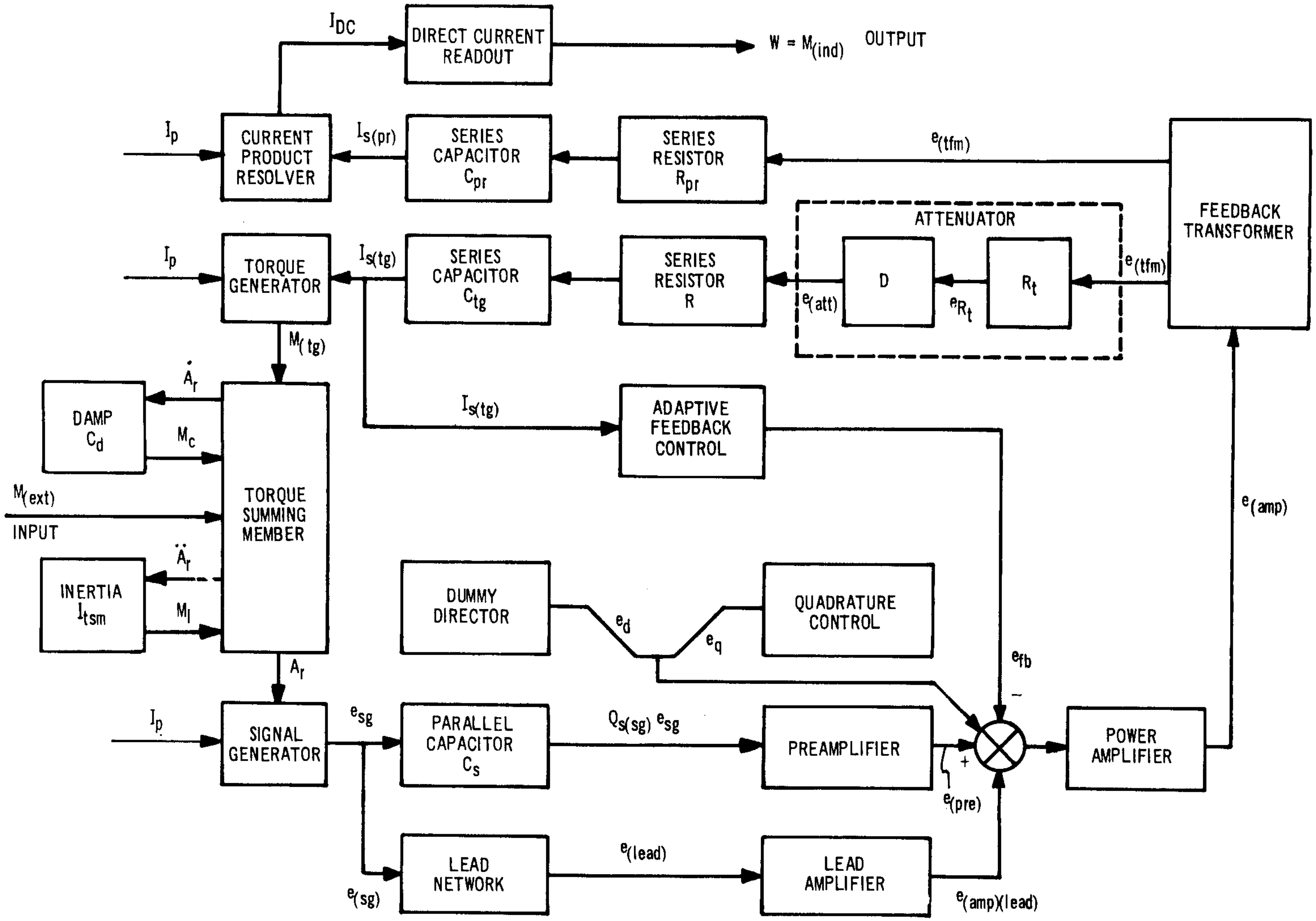


Fig. 9-6. Block diagram showing basic multirange adaptive elastance type of torque measuring system.

In conclusion, the authors feel that the marked success of this multirange precision torque measuring device is due to the following factors:

1. The current product transfer concept where the current-product input to the dynamometer type instrument is a direct measure of the current-product input to the microsyn torque generator, and is not a function of the excitation.
2. The adaptive elastance mode of operation which allows the dynamics of the measuring system to be automatically "adapted" to the particular torque level being considered.
3. The use of the attenuator-potentiometer together with the expanded full-scale null galvanometer in obtaining torque measurements to a high resolution.
4. The use of the "frictionless" air bearing which allows measurements of torque down to ± 0.0001 dyne-centimeters.

The proportional elastance system called the GS torque loop and the adaptive elastance system called the GDS torque loop represent a significant advance in the art of small torque measurements over a relatively large range of values. Possibly its finest application is in conjunction with the testing of the Draper floated integrating gyro with its magnetically supported floated gimbal. Here is a mating of two high precision pieces of hardware where each complements the other in obtaining some of the most accurate measurements of small torques that has ever been done.

BIBLIOGRAPHY

1. Draper, C. S., McKay, Walter, and Lees, Sidney, Instrument Engineering, McGraw-Hill Book Company, Inc., New York, 1952-1955.

2. Gilinson, P. J., Jr. and Scoppettuolo, J. A., An A-C Torque-to-Balance Measuring System, Report R-306, Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., June 1961.

3. Gilinson, P. J. Jr., Denhard, W. G., and Frazier, R. H., A Magnetic Support for Floated Inertial Instruments, Institute of the Aeronautical Sciences, S. M. F. Fund Paper No. FF-27, New York, May 1960.

4. Merrill, E. W., Non-Newtonianism In Thin Liquids, Ford Foundation Notes, Chemical Engineering Department, Massachusetts Institute of Technology, Cambridge, Mass, August 1961.

5. Modern Chemical Engineering, C. R. Wilkie, Editor, Reinhold Publishing Corp., New York (In Press).

6. Shin, H., The Rheology of Blood—Effect of Hematocrit and Temperature on Yield Value, B. S. Thesis, Chemical Engineering Department, Massachusetts Institute of Technology, Cambridge, Mass., June 1962.

7. Draper, C. S., Wrigley, Walter, and Hovorka, John, Inertial Guidance, Pergamon Press, New York-Oxford-London-Paris, 1960.

8. Wrigley, Walter, Single-Degree-of-Freedom Gyroscopes, Report R-375, Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., July 1962.